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Three issues pertaining to a possible amendment to the BSAI and GOA Groundfish FMPs addressing additional ACL-related aspects of the National Standard Guidelines

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Executive Summary

When Groundfish FMP Amendments 96(BSAI)/87(GOA) were being developed, it became apparent that some issues related to the treatment of annual catch limits (ACLs) in the National Standard 1 Guidelines were too complicated to address fully in those amendments, particularly given the stringent statutory deadlines for passage of those amendments. As a result, there was some anticipation that one or more trailing amendments might be considered. This discussion paper pertains to three issues (all with respect to the BSAI and GOA Groundfish FMPs) that might be addressed in such trailing amendments: 1) expanding or otherwise changing the role of scientific uncertainty in determining the buffer between ABC(=ACL) and OFL; 2) lack of a numeric value for MSST; and 3) possible ambiguities regarding which anthropogenic removals should be A) treated in computation of fishing mortality reference points and B) counted against harvest specifications.

As noted above, this paper is being provided for discussion purposes only. It is intended primarily for use by the SSC. If the SSC finds merit in any of the options put forward here, it may wish to study them further, perhaps through a subcommittee, a combination Team/SSC committee, or a workshop. It may also wish to take the formal step of proposing that one or more amendments to the Groundfish FMPs be developed. In the event that at least one FMP amendment is developed, it may be useful to identify *a priori* those elements that are strictly matters of policy, those elements that are strictly matters of science, and those elements that are a combination of the two. Given that the Secretary has already determined the Groundfish FMPs to be in substantial compliance with the National Standard 1 Guidelines as a result of Amendments 96(BSAI)/87(GOA), these issues can be addressed in a deliberative and thoughtful manner, with no need for imposition of a rigid timetable.

Some options for further analysis regarding issue #1, in addition to retaining the status quo, include the following:

1. Use the P^* approach by itself. Advantages: clearly complies with National Standard 1 Guidelines; buffer always increases with the level of uncertainty. Disadvantage: does not result in an optimal harvest level.

2. Use the decision-theoretic (DT) approach by itself. Advantage: results in an optimal harvest level. Disadvantages: compliance with National Standard 1 Guidelines is less clear than option #1 (on the other hand: "The decision-theoretic approach is very much 'allowed' in setting targets and limits"—Mark Millikin, NMFS Office of Sustainable Fisheries, pers. commun. 3/27/09); buffer does not always increase with the level of uncertainty, and can even be negative under some circumstances.

    a. One possible sub-option would be to use this approach to set an upper limit on TAC rather than ABC.

3. Use the DT approach constrained by the P^* approach (e.g., set maxABC at the minimum of the values prescribed by the two approaches). Advantages: results in an optimal harvest level except when the constraint is binding; clearly complies with National Standard 1 Guidelines. Disadvantages: does not result in an optimal harvest level when the constraint is binding; buffer does not always increase with the level of uncertainty.

    a. One possible sub-option would be to use this approach to set an upper limit on TAC rather than ABC.

Some options for further analysis regarding issue #2, in addition to retaining the status quo, include the following:

1. Specify MSST as the greater of: a) ½ B_{MSY}, or b) the smallest *equilibrium* stock size at which the stock would be expected to rebuild to B_{MSY} within 10 years if it were fished at F_{OFL} in each year. Advantages: fairly simple; proximity of the stock to MSST could be measured; management of BSAI and GOA groundfish would be more comparable to other U.S. fisheries; may provide additional protection for long-lived stocks. Disadvantages: depending on the age structure of the stock, could result in a stock being declared "overfished" even though the stock would be expected to rebuild to B_{MSY} within 10 years when fished at F_{OFL}.

2. Specify MSST as the greater of: a) ½ B_{MSY}, or b) the smallest *disequilibrium* stock size at which the stock would be expected to rebuild to B_{MSY} within 10 years if it were fished at F_{OFL} in each year. Advantages: proximity of the stock to MSST could be measured; management of BSAI and GOA groundfish would be more comparable to other U.S. fisheries; may provide additional protection for long-lived stocks; regardless of the age structure of the stock, would never result in a stock being declared "overfished" if the stock would be expected to rebuild to B_{MSY} within 10 years when fished at F_{OFL}. Disadvantages: very complicated; depending on the age structure of the stock, could result in a stock being declared "*not* overfished" even though the stock would *not* be expected to rebuild to B_{MSY} within 10 years when fished at F_{OFL}.

Some options for further analysis regarding issue #3, in addition to retaining the status quo, include the following:

1. Clarify how fishing mortality reference points should be computed when multiple sources of significant anthropogenic removals exist. Advantage: should reduce the possibility of misusing existing reference points. Disadvantage: may complicate the management process.

2. Clarify which anthropogenic removals should be counted against the various harvest specifications. Advantages: compliance with National Standard 1 Guidelines would be more obvious than at present. Disadvantages: knowing which removals should be counted against the specifications, by itself, does nothing to prevent those specifications from being exceeded; may complicate the management process.

3. Set TAC below ABC by an amount sufficient to keep total anthropogenic removals below ABC. Advantages: compliance with the National Standard 1 Guidelines would be more obvious than at present; total anthropogenic removals would likely not exceed ABC. Disadvantages: fewer fish would be available to the groundfish fishery; would almost certainly complicate the management process, including the setting of TACs and the authorization of research fishing.

4. Redefine ABC or ACL to be exclusive of certain types of anthropogenic removals. Advantages: might not require reductions in TAC in order to keep ABC/ACL from being exceeded (because some removals would not count). Disadvantages: total anthropogenic removals might still exceed OY or OFL (because the removals excluded from ABC/ACL would not be excluded from OY/OFL); compliance with the National Standard 1 Guidelines might not be obvious.

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Introduction

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As noted above, this paper is being provided for discussion purposes only. It is intended primarily for use by the SSC. If the SSC finds merit in any of the options put forward here, it may wish to study them further, perhaps through a subcommittee, a combination Team/SSC committee, or a workshop. It may also wish to take the formal step of proposing that one or more amendments to the Groundfish FMPs be developed. In the event that at least one FMP amendment is developed, it may be useful to identify *a priori* those elements that are strictly matters of policy, those elements that are strictly matters of science, and those elements that are a combination of the two. Given that the Secretary has already determined the Groundfish FMPs to be in substantial compliance with the National Standard 1 Guidelines as a result of Amendments 96(BSAI)/87(GOA), these issues can be addressed in a deliberative and thoughtful manner, with no need for imposition of a rigid timetable.

Issue #1: Expanding or otherwise changing the role of scientific uncertainty in determining the buffer between ABC(=ACL) and OFL

Some potentially relevant excerpts from the National Standard Guidelines

In the following, page numbers refer to the page of the Federal Register notice in which the current version of the guidelines for National Standard 1 were published (Vol. 74, No. 11; January 16, 2009).

p. 3208: (f)(2)(ii) *Acceptable biological catch (ABC)* is a level of a stock or stock complex’s annual catch that accounts for the scientific uncertainty in the estimate of OFL and any other scientific uncertainty..., and should be specified based on the ABC control rule.

p. 3208: (f)(2)(iii) *ABC control rule* means a specified approach to setting the ABC for a stock or stock complex as a function of the scientific uncertainty in the estimate of OFL and any other scientific uncertainty (see paragraph (f)(4) of this section).

p. 3209: (f)(4) *ABC control rule.* For stocks and stock complexes required to have an ABC, each Council must establish an ABC control rule based on scientific advice from its SSC. The determination of ABC should be based, when possible, on the probability that an actual catch equal to the stock’s ABC would result in overfishing. This probability that overfishing will occur cannot exceed 50 percent and should be a lower value…. The ABC control rule must articulate how ABC will be set compared to the OFL based on the scientific knowledge about the stock or stock complex and the scientific uncertainty in the estimate of OFL and any other scientific uncertainty. The ABC control rule should consider uncertainty in factors such as stock assessment results, time lags in updating assessments, the degree of retrospective revision of assessment results, and projections. The control rule may be used in a tiered approach to address different levels of scientific uncertainty.

Background and current FMP text

Background

December 1987: Amendment 11(BSAI) implemented. This amendment revised the definition of acceptable biological catch and added definitions for threshold and overfishing.

January 1991: Amendments 16(BSAI)/21(GOA) implemented. These amendments established the first tier system for defining overfishing, with OFL control rules shaped approximately as they are today.

January 1997: Amendments 44/44 implemented. These amendments imposed a buffer between F_{OFL} and $maxF_{ABC}$. The buffer varied directly with uncertainty for Tier 1, based on decision-theoretic considerations, while "fixed" buffers were used for Tiers 2-6. *This may have been the first use of a probability-based buffer between OFL and ABC anywhere in the U.S.*

March 1999: Amendments 56/56 implemented. These amendments instituted various changes intended to address the requirements of the 1998 version of the National Standard Guidelines. Changes included lowering the asymptote of the OFL control rules for Tiers 2-4 and the asymptote of the maxABC control rule for Tier 2 so that MSY was treated consistently as a limit rather than a target.

November 2010: Amendments 96(BSAI)/87(GOA) implemented. Among other things, these amendments mapped existing practices into the terminology used by the National Standard Guidelines.

Current FMP text

Overfishing Limit:

Specification of OFL begins with the MFMT (also known as the OFL control rule). The MFMT is prescribed through a set of six tiers which are listed below in descending order of preference, corresponding to descending order of information availability. The SSC will have final authority for determining whether a given item of information is "reliable" for the purpose of this definition, and may use either objective or subjective criteria in making such determinations.

For tier (1), a "pdf" refers to a probability density function. For tiers 1 and 2, if a reliable pdf of B_{MSY} is available, the preferred point estimate of B_{MSY} is the geometric mean of its pdf. For tiers 1 to 5, if a reliable pdf of B is available, the preferred point estimate is the geometric mean of its pdf. For tiers 1 to 3, the coefficient α is set at a default value of 0.05. This default value was established by applying the 10 percent rule suggested by Rosenberg et al. (1994) to the 1/2 B_{MSY} reference point. However, the SSC may establish a different value for a specific stock or stock complex as merited by the best available scientific information. For tiers 2 to 4, a designation of the form "$F_{X\%}$" refers to the fishing mortality rate (F) associated with an equilibrium level of spawning per recruit equal to $X\%$ of the equilibrium level of spawning per recruit in the absence of any fishing. If reliable information sufficient to characterize the entire maturity schedule of a species is not available, the SSC may choose to view spawning per recruit calculations based on a knife-edge maturity assumption as reliable. For tier 3, the term $B_{40\%}$ refers to the long-term average biomass that would be expected under average recruitment and $F=F_{40\%}$.

Tier 1 Information available: reliable point estimates of B and B_{MSY} and reliable pdf of F_{MSY} .

1a) Stock status: $B/B_{MSY} > 1$

$F_{OFL} = mA$, the arithmetic mean of the pdf

1b) Stock status: $\alpha < B/B_{MSY} \leq 1$

$F_{OFL} = mA \times (B/B_{MSY} - \alpha)/(1 - \alpha)$
1c) Stock status: $B/B_{MSY} \leq \alpha$
$F_{OFL} = 0$
Tier 2 Information available: reliable point estimates of B, B_{MSY} , F_{MSY} , $F_{35\%}$, and $F_{40\%}$.
2a) Stock status: $B/B_{MSY} > 1$
$F_{OFL} = F_{MSY}$
2b) Stock status: $\alpha < B/B_{MSY} \leq 1$
$F_{OFL} = F_{MSY} \times (B/B_{MSY} - \alpha)/(1 - \alpha)$
2c) Stock status: $B/B_{MSY} \leq \alpha$
$F_{OFL} = 0$
Tier 3 Information available: reliable point estimates of B, $B_{40\%}$, $F_{35\%}$, and $F_{40\%}$.
3a) Stock status: $B/B_{40\%} > 1$
$F_{OFL} = F_{35\%}$
3b) Stock status: $\alpha < B/B_{40\%} \leq 1$
$F_{OFL} = F_{35\%} \times (B/B_{40\%} - \alpha)/(1 - \alpha)$
3c) Stock status: $B/B_{40\%} \leq \alpha$
$F_{OFL} = 0$
Tier 4 Information available: reliable point estimates of B, $F_{35\%}$, and $F_{40\%}$.
$F_{OFL} = F_{35\%}$
Tier 5 Information available: reliable point estimates of B and natural mortality rate M.
$F_{OFL} = M$
Tier 6 Information available: reliable catch history from 1978 through 1995.
OFL = the average catch from 1978 through 1995, unless an alternative value is established by the SSC on the basis of the best available scientific information

Acceptable Biological Catch:

Specification of ABC is similar to specification of OFL, in that both involve harvest control rules with six tiers relating to various levels of information availability. However, somewhat more flexibility is allowed in specifying ABC, in that the control rule prescribes only an upper bound. The steps are as follow:

1. Determine the appropriate tier (this will be the same tier used to specify OFL).
2. Determine the maximum permissible ABC fishing mortality rate from the appropriate tier of the ABC control rule (see below).
3. Except for stocks or stock complexes managed under Tier 6, compute the maximum permissible ABC by applying the maximum permissible ABC fishing mortality rate to the best estimate of stock size (which may or may not be age structured); for stocks and stock complexes managed under Tier 6, the control rule automatically produces a maximum permissible ABC, so application of a fishing mortality rate is unnecessary.
4. Determine whether conditions exist that warrant setting ABC at a value lower than the maximum permissible value (such conditions may include—but are not limited to—data uncertainty, recruitment variability, and declining population trend) and, if so:
    a. document those conditions,
    b. recommend an ABC lower than the maximum permissible value, and
    c. explain why the recommended value is appropriate.

The above steps are undertaken first by the assessment authors in the individual chapters of the SAFE report. The Plan Team then reviews the SAFE report and makes its own recommendation. The SSC then reviews the SAFE report and Plan Team recommendation, and makes its own recommendation to the Council. The Council then reviews the SAFE report, Plan Team recommendation, and SSC recommendation; then makes its own recommendation to the Secretary, with the constraint that the Council‘s recommended ABC cannot exceed the SSC‘s recommended ABC.

The ABC control rule is as follows (definitions of terms and information requirements for the six tiers are identical to those used in the OFL control rule):

Tier 1 Information available: reliable point estimates of B and B_{MSY} and reliable pdf of F_{MSY} .
  1a) Stock status: $B/B_{MSY} > 1$
    $maxF_{ABC} = mH$, the harmonic mean of the pdf
  1b) Stock status: $\alpha < B/B_{MSY} \leq 1$
    $maxF_{ABC} = mH \times (B/B_{MSY} - \alpha)/(1 - \alpha)$
  1c) Stock status: $B/B_{MSY} \leq \alpha$
    $maxF_{ABC} = 0$
Tier 2 Information available: reliable point estimates of B, B_{MSY} , F_{MSY} , $F_{35\%}$, and $F_{40\%}$.
  2a) Stock status: $B/B_{MSY} > 1$
    $maxF_{ABC} = F_{MSY} \times (F_{40\%}/F_{35\%})$
  2b) Stock status: $\alpha < B/B_{MSY} \leq 1$
    $maxF_{ABC} = F_{MSY} \times (F_{40\%}/F_{35\%}) \times (B/B_{MSY} - \alpha)/(1 - \alpha)$
  2c) Stock status: $B/B_{MSY} \leq \alpha$
    $maxF_{ABC} = 0$
Tier 3 Information available: reliable point estimates of B, $B_{40\%}$, $F_{35\%}$, and $F_{40\%}$.
  3a) Stock status: $B/B_{40\%} > 1$
    $maxF_{ABC} = F_{40\%}$
  3b) Stock status: $\alpha < B/B_{40\%} \leq 1$
    $maxF_{ABC} = F_{40\%} \times (B/B_{40\%} - \alpha)/(1 - \alpha)$
  3c) Stock status: $B/B_{40\%} \leq \alpha$
    $maxF_{ABC} = 0$
Tier 4 Information available: reliable point estimates of B, $F_{35\%}$, and $F_{40\%}$.
    $F_{OFL} = F_{40\%}$
Tier 5 Information available: reliable point estimates of B and natural mortality rate M.
    $F_{OFL} = 0.75 \times M$
Tier 6 Information available: reliable catch history from 1978 through 1995.
    maxABC = 0.75 × OFL

The above control rule is intended to account for scientific uncertainty in two ways: First, the control rule is structured explicitly in terms of the type of information available, which is related qualitatively to the amount of scientific uncertainty. Second, the size of the buffer between $maxF_{ABC}$ in Tier 1 of the ABC control rule and F_{OFL} in Tier 1 of the OFL control rule varies directly with the amount of scientific uncertainty. For the information levels associated with the remaining tiers, relating the buffer between $maxF_{ABC}$ and F_{OFL} to the amount of scientific uncertainty is more difficult because the amount of scientific uncertainty is harder to quantify, so buffers of fixed size are used instead.

For groundfish species identified as key prey of Steller sea lions (i.e., walleye pollock, Pacific cod, and Atka mackerel), directed fishing is prohibited in the event that the spawning biomass of such a species is projected in the stock assessment to fall below $B_{20\%}$ in the coming year. However, this does not change the specification of ABC or OFL.

Analysis

Notational convention: In this section, the symbol $p(\cdot)$ represents an arbitrary probability density function. Use of the same name for probability density functions of different random variables (e.g., $p(x)$ and $p(y)$) is not meant to imply that p takes the same form in each instance.

Derivation of the Tier 1 control rules

The current Tier 1 maxABC control rule was developed using decision theory (DT). Specifically, the control rule was based on the Fox (1970) model, generalized to stochastic form (Thompson 1998), with a utility function exhibiting constant relative risk aversion (Pratt 1964; Arrow 1965, 1971).

The Fox model can be written

$$\frac{dB}{dt} = Fmsy \cdot B \cdot \left(1 - \ln\left(\frac{B}{Bmsy}\right)\right) - F \cdot B \quad ,$$

Where B = stock size, t = time, F = fishing mortality rate, $Fmsy$ = fishing mortality rate that sets equilibrium (“sustainable”) yield equal to maximum sustainable yield (MSY), and $Bmsy$ = equilibrium stock size at MSY.

This model gives the following solution for equilibrium yield Y:

$$Y = F \cdot Bmsy \cdot \exp\left(1 - \frac{F}{Fmsy}\right) \quad .$$

Equilibrium yield can be normalized to units of “relative yield” RY by expressing it relative to $MSY{=}Fmsy{\cdot}Bmsy$ as follows:

$$RY = \left(\frac{F}{Fmsy}\right) \cdot \exp\left(1 - \frac{F}{Fmsy}\right) \quad .$$

If relative yield is adopted as the measure of nominal wealth accruing to society from the fishery, the utility (U) function exhibiting constant relative risk aversion can be written

$$U = \frac{RY^{\,1-RRA} - RRA}{1 - RRA} \quad ,$$

where RRA is the level of relative risk aversion (a real-valued parameter).

Some examples of the constant RRA utility function are shown in Figure 1. In general, concave functions are risk averse (RRA>0), the linear case represents risk neutrality (RRA=0), and convex functions are risk prone (RRA<0).

A convenient feature of the constant RRA utility function is that maximization of expected utility is equivalent to maximizing an order mean of the argument. An order mean is a root of a non-central moment. For example, if $p(Fmsy)$ represents the pdf of $Fmsy$, the zth order mean of RY is

$$\mu_{RY}(F,z)=\left(\int_0^\infty p(Fmsy)\cdot\left(\left(\frac{F}{Fmsy}\right)\cdot\exp\left(1-\frac{F}{Fmsy}\right)\right)^z dFmsy\right)^{1/z} \quad .$$

Familiar special cases of order means include the arithmetic mean (z = 1), geometric mean (reached in the limit as z approaches 0), and harmonic mean (z = −1).

When the utility function is of the constant RRA form, expected utility is given by

$$EU(F,RRA)=\frac{\mu_{RY}(F,1-RRA)^{1-RRA}-RRA}{1-RRA} \quad .$$

Thus, maximizing expected utility, given a specified value of *RRA*, is equivalent to maximizing the mean (of *RY*) of order 1−*RRA*.

The special case where *RRA* approaches unity in the limit corresponds to U=1+ln(*RY*). This special case is often used as an archetype of risk aversion, and was the utility function used to develop the Tier 1 maxABC control rule. If *RRA*=1, the optimal harvest rate is determined by maximizing the geometric mean (1−*RRA* = 0) of *RY*.

In the special case of the Fox model where *Fmsy* is viewed as a random variable because of scientific uncertainty, the geometric mean of *RY* involves order means of *Fmsy* (note the distinction between order means of *RY* and order means of *Fmsy*). Let the geometric and harmonic means of *Fmsy* be written

$$G_{Fmsy}=\exp\left(\int_0^\infty p(Fmsy)\cdot\ln(Fmsy)\,dFmsy\right) \quad ,$$

and

$$H_{Fmsy}=\left(\int_{-\infty}^\infty p(Fmsy)\cdot Fmsy^{-1}dFmsy\right)^{-1} \quad ,$$

respectively. Then, the geometric mean of *RY* can be written

$$\mu_{RY}(F,0)=\left(\frac{F}{G_{Fmsy}}\right)\cdot\exp\left(\frac{F}{H_{Fmsy}}\right) \quad .$$

The derivative of the above with respect to *F* is

$$\frac{d\mu_{RY}(F,0)}{dF}=\mu_{RY}(F,0)\cdot\left(\frac{1}{F}-\frac{1}{H_{Fmsy}}\right) \quad ,$$

which equals zero only at $F=H_{Fmsy}$. Note that this result holds regardless of the functional form of $p(Fmsy)$.

Although the deriviation of the harmonic mean of *Fmsy* as the risk-averse (specifically, *RRA*=1) optimal harvest rate was based on a single model (the Fox model), it was also tested against the model of Thompson (1992) to determine whether it was a reasonably robust estimator of the risk-averse optimal harvest rate when the underlying assumptions of the original analysis were violated. Thompson (1992) derived the optimal fishing mortality rate for a simple model when the exponent (q) in the Cushing (1971) stock-recruitment relationship was uncertain, given *RRA*=1. If the problem is re-cast in terms of the *resilience* ($r \equiv 1-q$) of the stock-recruitment relationship, it turns out that the optimal harvest rate under uncertainty is identical to the optimal harvest rate under certainty, where the latter is evaluated at the harmonic mean of r. Because the certainty-equivalent value of *Fmsy* is a nonlinear function of r in this model, the harmonic mean of *Fmsy* itself and the value of *Fmsy* at the harmonic mean of r will be equal only in special cases. However, the analysis conducted in developing Amendments 44/44 indicated that, although the harmonic mean of *Fmsy* was seldom exactly equal to the optimal harvest rate in the model of Thompson (1992), it was almost always reasonably close.

The above derivation deals with use of the harmonic mean *Fmsy* as the asymptote of the Tier 1 maxABC control rule. In contrast to the formal derivation of this reference point, it should be noted that use of the arithmetic mean *Fmsy* as the asymptote of the Tier 1 OFL control rule was largely *ad hoc*, and should not be confused with the risk-neutral optimum F. The main reasons for using the arithmetic mean *Fmsy* in this way are that it is unambiguously larger than the harmonic mean, and that it is a fairly natural choice for a single statistic describing the central tendency of *Fmsy*.

<u>Sometimes optimality is not intuitive</u>

The EA for the ACL amendment to the Crab FMP raised some questions about the DT approach in general, because the risk-averse and risk-neutral optima computed in some of the examples were very close to each other, despite the presence of a large level of uncertainty surrounding key model parameters.

Although use of the harmonic and arithmetic means of *Fmsy* to specify the asymptotes of the maxABC and OFL control rules does guarantee that $maxF_{ABC}$ is always less than F_{OFL}, and does guarantee that the buffer between $maxF_{ABC}$ and F_{OFL} increases with uncertainty (given an appropriate measure thereof), these are not features of the DT approach in general, which may pose a potential problem for expanded use of the latter. More specifically, under certain circumstances, uncertainty surrounding the true value of *Fmsy* can result in a risk-averse optimal F that exceeds the risk-neutral optimal F, the arithmetic mean of *Fmsy*, or both.

An example where the risk-averse optimal F exceeds the risk-neutral optimal F can be developed in the context of the simple Schaefer (1954) model. The Schaefer model is usually parameterized as:

$$\frac{dB}{dt} = r \cdot B \cdot \left(1 - \frac{B}{K}\right) - F \cdot B \quad ,$$

where r = intrinsic rate of increase and K = carrying capacity. In this model, $Bmsy=K/2$ and $Fmsy=r/2$, giving $MSY=r \cdot K/4$.

Equilibrium yield in the Schaefer model is given by:

$$Y = F \cdot K \cdot \left(1 - \frac{F}{r}\right) \quad .$$

Equilibrium yield can be normalized to units of *RY* by expressing it relative to *MSY* as follows:

$$RY = \left(\frac{F}{Fmsy}\right)\cdot\left(2-\frac{F}{Fmsy}\right) \quad .$$

Consider the (very) hypothetical scenario where 0.2 and 0.4 are the only possible values of *Fmsy*, with these values being equally probable. The relative yields are plotted in Figure 2 for values of *F* less than or equal to 0.4, with the relative yield for $Fmsy_1$ denoted by the blue curve and the relative yield for $Fmsy_2$ denoted by the red curve (note that the lower end of vertical axis in the figure is truncated at a value of 0.8). The two relative yield curves intersect at the point identified by the magenta dashed lines in the figure, with abscissa and ordinate given by

$$F_{int} = 2\cdot\left(\frac{Fmsy_1\cdot Fmsy_2}{Fmsy_1+Fmsy_2}\right) = 4/15 \approx 0.267$$

and

$$RY_{int} = 2\cdot\left(\frac{F_{int}}{Fmsy_1+Fmsy_2}\right) = 8/9 \approx 0.889 \quad ,$$

respectively.

The arithmetic mean relative yield is shown by the green curve in Figure 2. The risk-neutral optimal *F* corresponds to the maximum of the green curve, as indicated by the green dashed lines, with abscissa and ordinate given by

$$F_{neutral} = \frac{\frac{1}{Fmsy_1}+\frac{1}{Fmsy_2}}{\frac{1}{Fmsy_1^{\,2}}+\frac{1}{Fmsy_2^{\,2}}} = 0.24$$

and

$$RY_{neutral} = \frac{\left(Fmsy_1+Fmsy_2\right)^2}{2\cdot\left(Fmsy_1^{\,2}+Fmsy_2^{\,2}\right)} = 0.9 \quad ,$$

respectively.

A fuller description of this example is given below, but for now, a simple explanation of the phenomenon can be provided as follows: The risk-neutral manager will seek to maximize the expected relative yield (i.e., the arithmetic mean *RY*). This is achieved by fishing at the $F_{neutral}$ rate given above. However, an *utterly* risk-averse manager (i.e., a manager who sets $RRA = \infty$) will seek to maximize the value of the worst-case scenario (the "maximin" solution, in the language of game theory). If the stock is fished at the $F_{neutral}$ rate, Figure 2 shows that two outcomes are possible: the relative yield will equal 0.96 if $Fmsy_1$ (=0.2) is the true value of *Fmsy* (blue dashed line), but the relative yield will equal only 0.84 if $Fmsy_2$

(=0.4) is the true value of *Fmsy* (red dashed line). The utterly risk-averse manager can do better at any value of *F* between $F_{neutral}$ and F_{int}, because RY_2 (red curve) increases monotonically with *F* while remaining less than RY_1 (blue curve) throughout this range. Such increases in the worst-case outcome are always accompanied here by decreases in the best-case outcome, but an *utterly* risk-averse manager will not care about this. In the limiting case where the stock is fished at the F_{int} rate, the worst-case and best-case scenarios are identical and equal to RY_{int}. If the stock is fished at any rate higher than F_{int}, the worst-case scenario will be given by RY_1 (blue curve) instead of RY_2 (red curve), and will be lower than RY_{int}. Therefore, F_{int} is the optimal fishing mortality rate for an utterly risk-averse manager. However, F_{int} is clearly greater than $F_{neutral}$, meaning that this is one situation in which a risk-averse optimal *F* is higher than the risk-neutral optimal *F*.

A fuller analysis of this example can begin by considering the case where *RRA*=1. In this case, the optimal *F* maximizes the *geometric* mean of *RY*, and is given by

$$F_{RRA=1} = \frac{3\cdot\left(Fmsy_1 + Fmsy_2\right) - \sqrt{9\cdot\left(Fmsy_1 + Fmsy_2\right)^2 - 32\cdot Fmsy_1\cdot Fmsy_2}}{4} \approx 0.244 \quad ,$$

which results in a geometric mean *RY* value of approximately 0.898.

Thus, the optimal *F* for *RRA*=1 exceeds the risk-neutral optimal *F* in this example. Figure 3 expands on this result by considering a wide range of *RRA* values (the range of values shown in Figure 3a is a subset of those shown in Figure 3b). Note that the optimal *F* increases monotonically with *RRA* throughout the range. In the limit as *RRA* approaches $-\infty$, the optimal *F* approaches $Fmsy_1$; while in the limit as *RRA* approaches ∞, the optimal *F* approaches F_{int}. Figures 4 and 5 show two additional ways of viewing these results. Figure 4 adds to Figure 2 by showing the locus of maximum values for all order means ranging from $-\infty$ to ∞ and their corresponding fishing mortality rates (black curve). Figure 5 shows how the *RY* means of order -1, 0, 1, and 2 vary with *F* (purple, green, orange, and light blue curves, respectively); along with the locus of maximum values for all order means ranging from approximately -2 to ∞ and their corresponding fishing mortality rates (black curve).

As an aside, it might be noted that two of the original papers deriving the $F_{35\%}$ and $F_{40\%}$ reference points (Clark 1991, Clark 1993), made explicit use of the maximin strategy, which, in light of the above result wherein the maximin strategy corresponded to an utterly risk averse attitude, might lead one to conclude that the $F_{35\%}$ and $F_{40\%}$ reference points are highly risk averse. In fact, this conclusion is exactly correct *given* the constraints imposed in those original papers on the admissible range of shapes for the stock-recruitment relationship. However, if those constraints were relaxed so as to admit the full range of shapes that might result from statistical estimation of actual stock-recruitment relationships, neither $F_{35\%}$ nor $F_{40\%}$ would correspond to the utterly risk averse optimum (although one or both might still imply some positive level of risk aversion).

<u>The *P** alternative</u>

The *P** approach (e.g., Prager et al. 2003) involves some of the same information used in the DT approach. If the objective is simply to set $maxF_{ABC}$, then the approach consists of the following equation for $maxF_{ABC}$, given a value for the policy parameter *P**:

$$P^* = \int_0^{maxF_{ABC}} p\left(Fmsy\right) dFmsy \quad .$$

The *P** approach was analyzed at length in the EA for the ACL amendment to the Crab FMP. It is therefore somewhat familiar in the NPFMC arena, has been used widely in other U.S. fisheries, and is a straightforward implementation of the language used in the National Standard Guidelines. However, its optimality properties are indirect at best, and nonexistent at worst. Simply put, there is no straightforward relationship between an ABC based on the *P** approach and an optimal harvest level. This is because the *P** approach is not designed with optimization in mind; rather, its objective is to achieve a constant probability of obtaining a single undesired outcome (in the present context, the undesired outcome is an ABC that exceeds the *true but unknown* OFL—as distinguished from the OFL that is actually specified). A simple analogy may help to illustrate this. Suppose that two urns, labeled "A" and "B," each contain 60 white balls and 40 black balls, thoroughly mixed, and suppose that an individual is given the opportunity to choose one of the two urns and draw one ball from that urn. If a white ball is drawn, the individual wins a prize, but if a black ball is drawn, the individual incurs a penalty. If urn A is chosen, the prize is $1,000,000 and the penalty is $1. If urn B is chosen, the prize is $1 and the penalty is $1,000,000. In the DT approach, use of any reasonable utility function would lead the individual to choose urn A. In the *P** approach, however, there is no value of *P** that would allow the individual to determine a preference between the two urns, because the probability of obtaining an undesired outcome is exactly the same for both urns. For any value of $P^*\geq 40\%$, the individual will be completely indifferent between the two urns, and for any value of $P^*<40\%$, the individual will reject *both* urns. Likewise, achieving a constant probability of ABC exceeding the true but unknown OFL has very little necessary relationship to optimal management of the fishery, in part because this makes no allowance for either the magnitude of the overage or the consequences of the overage, and in part because this makes no allowance for what is gained or lost by setting the harvest rate equal to the $maxF_{ABC}$ dictated by the particular choice of *P**.

One question that has often been asked is, "Why not just use the value of *P** that sets the ABC from the *P** approach equal to the ABC from the DT approach?" The answer is twofold: First, this would amount to using the DT approach, but with some completely superfluous steps added. It would be much simpler just to use the DT approach without the additional steps. Second, this would likely require setting a different value of *P** for every stock; moreover, these stock-specific values of *P** would likely change every time a new assessment is conducted. For example, using the current Tier 1 maxABC control rule, the "DT-equivalent" value of *P** depends strongly on both the functional form and the coefficient of variation (CV) of the *Fmsy* pdf. Figure 6 shows how the DT-equivalent value of *P** varies with CV for lognormal and gamma distributions (the means of the distributions cancel, and so do not affect the result). In the limit as CV approaches 0, both distributions set the DT-equivalent *P** value at 0.5, but they diverge for positive values of CV. The DT-equivalent value of *P** falls to zero when CV=1 in the gamma case, while the DT-equivalent value of *P** is greater than 0.2 for all values of CV<4 in the lognormal case. In practice, perhaps the best that could be hoped for would be to find the value of *P** that came closest to matching the results of the DT approach averaged across all stocks (perhaps weighted by biomass, revenue, or something else).

<u>Some questions remaining to be answered</u>

One ambiguity that was not thoroughly discussed during the development of Amendments 44/44 was how the harmonic mean rule was to be interpreted when uncertainty existed regarding the values of parameters other than *Fmsy* (e.g., selectivity). For the past few years, assessments of Tier 1 species have interpreted *Fmsy* as the ratio of *MSY* to *Bmsy*, which is consistent with the interpretation of *Fmsy* used in the original analysis, but which may cause confusion if there is a similarly named parameter in the model that represents the *full selection* fishing mortality rate. If the buffer between ABC and OFL is to be addressed in a future FMP amendment, this is an area for possible improvement.

For either the DT or *P** approach, attention should be given to the possibility of extending the use of probability-based buffers to tiers other than Tier 1, or to the possibility of restructuring existing assessment models so that more stocks qualify for management under Tier 1. Now that all stocks managed under Tier 3 are assessed with models based on ADMB, variance estimates should be obtainable for all estimated parameters and derived quantities, in which case all that is required for use of either the DT or *P** approach would be specification of the necessary functional forms and parameters (see paragraphs immediately following). The alternative strategy of restructuring existing assessment models so that more stocks qualify for management under Tier 1 should also be feasible. One way to accomplish this is to adopt an explicitly Bayesian approach, with well-rationalized prior distributions (particularly for the stock-recruitment parameters, or perhaps stock-recruitment parameters could be aliased by *Fmsy* and *Bmsy* or MSY, as was done by Schnute and Kronlund (1996), Schnute and Richards (1998), and Forrest et al. (2008)).

Expanded use of the DT approach would require specification of a loss function and any parameters involved therein. For example, the utility function described above would require specifying the value of *RRA* to be used in the maxABC control rule (and the OFL control rule, if desired). Alternative functional forms for the utility function could also be considered. For example, a utility function exhibiting constant *absolute* (as opposed to relative) risk aversion, *ARA*, is another common choice:

$$U = \frac{1 - \exp(-ARA \cdot RY)}{\exp(ARA) - 1} \quad .$$

The constant *RRA* and constant *ARA* utility functions are useful because they are simple, well known, and have convenient statistical properties. However, these are by no means the only possible choices. Rather, the utility function can take whatever form is necessary to achieve an accurate representation of utility. This begs the question of *whose* utility is to be represented: the Council's, the Secretary's, the Nation's, other? Also, in the discussion so far, the argument of the utility function has been taken to be equilibrium relative yield (*RY*), but this is not the only possible choice. Instead of focusing only on yield in the equilibrium state, the utility function might also consider yields realized *en route* to equilibrium (probably in combination with some positive discount rate); it might use revenue or profit instead of yield; and it might consider existence value, option value, or consumer surplus in addition to revenue or profit. Along these lines, the SSC made the following suggestion at its February 2011 meeting in response to a presentation by Michael Dalton on maximum economic yield (*MEY*) and *MSY* in the crab fishery: "To the extent practicable, the analysis of *MEY*/*MSY* should be incorporated into Grant Thompson's decision theoretic approach, as part of the review of groundfish ACLs." Although *MEY* concepts have not yet been integrated into the DT approach for setting maxABC (except to the extent that utility itself is defined as an economic concept), a discussion of ACLs vis-à-vis *MEY* is included here as an appendix. Of course, more complicated utility functions will typically require more parameters to be specified, more data to be gathered, and more complicated models to be developed. (Note: although the derivation of the current Tier 1 maxABC control rule was based on a constant *RRA* utility function with *RRA*=1, the FMP itself does not specify a utility function.)

In contrast, to begin using the *P** approach, the only parameter that needs to be specified is *P** itself, *provided that all relevant uncertainty has been quantified* (see next paragraph). Although the number of parameters that need to be specified in the *P** approach is small, the specification process can be very difficult because of the lack of correspondence between the value of *P** and any optimization-based management objective, as discussed above.

Another issue for both the *P** and DT approaches is how to deal with uncertainty that has not been quantified statistically (referred to as "σ_B" in the EA for the ACL amendment to the Crab FMP). For example, the statistical age-structured assessments currently used for all groundfish stocks managed under Tiers 1-3 provide variance estimates for model parameters and derived quantities, but these are all conditional on a particular model, and do not consider uncertainty in the assumptions underlying the model itself (functional forms, etc.). Some possibilties:

1. Consider only whatever uncertainty can be quantified statistically. Advantages: no new methodology necessary; no need to develop *ad hoc* variance adjustments. Disadvantages: true total uncertainty will likely be underestimated; models with more/stronger assumptions will have smaller uncertainty than models with fewer/weaker assumptions (i.e., the amount of uncertainty can be decreased or increased simply by adopting a simpler or more complicated model).
2. Inflate whatever uncertainty is currently estimated statistically by some agreed-upon but ultimately *ad hoc* amount. Advantages: could likely be implemented in the near future; will not underestimate true total uncertainty by as much as option #1. Disadvantages: the precise amounts of the *ad hoc* adjustments will be difficult to justify; resulting estimates may either systematically underestimate or systematically overestimate true total uncertainty.
3. Develop statistical approaches for quantifying all presently non-quantified uncertainty. Advantage: provides an accurate estimate of true total uncertainty. Disadvantage: the necessary methodology may take a long time—or even prove impossible—to develop.

Finally, for either the DT or *P** approach, a choice needs to be made as to whether the maxABC and OFL control rules determine *fishing mortality rates* or *removal amounts*. This choice is easily illustrated using the *P** approach, which can be used to determine either quantity by choosing the appropriate equation from the following pair and solving for the upper limit of the integral:

$$P^* = \int_0^{maxF_{ABC}} p(Fmsy)\,dFmsy \quad ,$$

$$P^* = \int_0^{maxABC} p(OFL)\,dOFL \quad .$$

The current control rules prescribe fishing mortality rates only. If every other relevant quantity (e.g., stock size, age structure, selectivity) is known precisely, these fishing mortality rates translate into removal amounts without any ambiguity. When other relevant quantities involve significant uncertainty, however, it is not obvious how these additional uncertainties should be incorporated into computation of maxABC and OFL under the current system. Conversely, if the control rules are expressed in terms of removal amounts, it may be difficult to infer "the" fishing mortality rates to which they correspond.

Some options for future consideration

Some options for further analysis regarding issue #1, in addition to retaining the status quo, include the following (any relevant items among the "some questions remaining to be answered" above should be addressed regardless of which option is chosen):

1. Use the *P** approach by itself. Advantages: clearly complies with National Standard 1 Guidelines; buffer always increases with the level of uncertainty. Disadvantage: does not result in an optimal harvest level.

2. Use the DT approach by itself. Advantage: results in an optimal harvest level. Disadvantages: compliance with National Standard 1 Guidelines is less clear than option #1 (on the other hand: "The decision-theoretic approach is very much 'allowed' in setting targets and limits"—Mark Millikin, NMFS Office of Sustainable Fisheries, pers. commun. 3/27/09); buffer does not always increase with the level of uncertainty, and can even be negative under some circumstances.

    a. One possible sub-option would be to use this approach to set an upper limit on TAC rather than ABC.

3. Use the DT approach constrained by the *P** approach (e.g., set maxABC at the minimum of the values prescribed by the two approaches). Advantages: results in an optimal harvest level except when the constraint is binding; clearly complies with National Standard 1 Guidelines. Disadvantages: does not result in an optimal harvest level when the constraint is binding; buffer does not always increase with the level of uncertainty.

    a. One possible sub-option would be to use this approach to set an upper limit on TAC rather than ABC.

Issue #2: Lack of a numeric value for MSST

Some potentially relevant excerpts from the National Standard Guidelines

In the following, page numbers refer to the page of the Federal Register notice in which the current version of the guidelines for National Standard 1 were published (Vol. 74, No. 11; January 16, 2009).

p. 3206: (e)(2)(i)(A) *Status determination criteria* (SDC) mean the quantifiable factors, MFMT, OFL, and MSST, or their proxies, that are used to determine if overfishing has occurred, or if the stock or stock complex is overfished.

p. 3206: (e)(2)(i)(F) *Minimum stock size threshold* (MSST) means the level of biomass below which the stock or stock complex is considered to be overfished.

p. 3206: (e)(2)(ii)(B) *SDC to determine overfished status.* The MSST or reasonable proxy must be expressed in terms of spawning biomass or other measure of reproductive potential. To the extent possible, the MSST should equal whichever of the following is greater: One-half the MSY stock size, or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years, if the stock or stock complex were exploited at the MFMT specified under paragraph (e)(2)(ii)(A)(1) of this section. Should the estimated size of the stock or stock complex in a given year fall below this threshold, the stock or stock complex is considered overfished.

Background and current FMP text

<u>Background</u>

April 1998: The SSC concluded, "The Council policy of using a biomass-based policy that reduces fishing mortality as stocks decrease in size was deliberately selected to provide for automatic rebuilding.... The added complexity of a threshold policy on top of a biomass-based policy serves no useful purpose, is harder to implement, and will be harder for the public to understand. The current stock assessment approach is sufficient to assure that harvest levels provide for sufficient rebuilding within the specified period of 10 years...."

June 1998: Amendments 56/56 approved by the Council. These amendments would institute various changes intended to address the requirements of the 1998 version of the National Standard Guidelines. Changes included lowering the asymptote of the OFL control rules for Tiers 2-4 and the asymptote of the maxABC control rule for Tier 2 so that MSY was treated consistently as a limit rather than a target, but *did not* include specifying MSST.

March 1999: Amendments 56/56 implemented. Secretarial approval had been granted with the understanding that these amendments contained a proxy for MSST and that $B_{40\%}$ corresponded to the MSY level in Tier 3. The MSST proxy involved shifting the intercept of the OFL control rule on a case-by-case basis such that rebuilding to the MSY level would be expected within 10 years even if catches were set equal to the value associated with the OFL control rule in each year. However, this proxy had not been considered by either the SSC or the Council and had not been tested at the time of approval.

April-July 1999: The MSST proxy envisioned by the Secretary when Amendments 56/56 were approved turned out to be highly impractical, resulting in OFLs of zero for some stocks that were only modestly below $B_{40\%}$. Many alternative methods for interpreting or revising Amendments 56/56 were then examined for each stock managed under Tiers 1-3.

August 1999: NMFS revised its interpretation of Amendments 56/56, and decided upon a strategy to be used in completing the required status determination report (the "Report to Congress"). Major features included the following: 1) an MSST was used for all stocks managed under Tiers 1-3; 2) $B_{35\%}$ was used as the proxy for the MSY level in Tier 3 (this did not involve a change in the control rule, but rather an interpretation as to when a stock would be considered "rebuilt"); 3) a "regime shift" commencing in 1977 was recognized, meaning that all recruitment time series were standardized such that no year classes spawned prior to 1977 were included; and 4) a simulation approach was used to determine whether the stock would be expected to rebuild to B_{MSY} (Tiers 1-2) or the B_{MSY} proxy (Tier 3) within 10 years if fished at the OFL control rule.

November 2010: Amendments 96(BSAI)/87(GOA) implemented. Among other things, these amendments finally formalized the procedure outlined above, which had been used in all SAFE reports since 1999.

<u>Current FMP text</u>

Definition of Terms:

Minimum stock size threshold (MSST) is the level of biomass below which the stock or stock complex is considered to be overfished. To the extent possible, the MSST should equal whichever of the following is greater: One-half the MSY stock size, or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years, if the stock or stock complex were exploited at the MFMT.

Determination of "Overfished" Status:

A stock or stock complex is determined to be "overfished" if it falls below the MSST. According to the National Standard Guidelines definition, the MSST equals whichever of the following is greater: One-half the MSY stock size, or the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years, if the stock or stock complex were exploited at the MFMT.

The above definition raises two questions: 1) How is the definition to be applied when "the MSY level" cannot be estimated? 2) In the context of an age-structured assessment, what is the meaning of the phrase, "the minimum stock size at which rebuilding to the MSY level would be expected to occur within 10 years?" These questions are addressed in this FMP as follows:

1. Direct estimates of B_{MSY} (i.e., "the MSY level") are available for Tiers 1 and 2. For Tier 3, no direct estimate of B_{MSY} is available, but $B_{35\%}$ is used as a proxy for B_{MSY}. For Tiers 4-6, neither direct estimates of B_{MSY} nor reliable estimates of B_{MSY} proxies are available. Therefore, the "overfished" status of stocks and stock complexes managed under Tiers 4-6 is *undefined*.

2. For a stock assessed with an age-structured model (as is typically the case for stocks and stock complexes managed under Tiers 1-3), there is more than one stock size or numbers-at-age vector at which rebuilding to the MSY level would be expected to occur in exactly 10 years. Generally, there is no limit to the range of numbers-at-age vectors that satisfy this constraint, and each of these vectors corresponds to a stock size. Therefore, stock status in Tiers 1-3 is determined annually as follows: The determination of "overfished" status begins with an estimate of the stock's "current spawning biomass," which is defined as the estimated spawning biomass for the "current year," which in turn is defined as the most recent year from which data are used in the assessment. Given these definitions, and with the understanding that $B_{35\%}$ is used as a proxy for B_{MSY} in Tier 3, the determination proceeds as follows:

    a. If current spawning biomass is estimated to be below ½ B_{MSY}, the stock is below its MSST.

    b. If current spawning biomass is estimated to be above B_{MSY} the stock is above its MSST.

    c. If current spawning biomass is estimated to be above ½ B_{MSY} but below B_{MSY}, then conduct a large number of stochastic simulations by projecting the numbers-at-age vector from the current year forward under the assumption that it will be fished at the MFMT in every year, and determine status as follows:

        i. If the mean spawning biomass in the 10th year beyond the current year is below B_{MSY}, the stock is below its MSST.

        ii. Otherwise, the stock is above its MSST.

Analysis

Why is this an issue?

Although the current MSST definition is taken directly from the National Standard Guidelines, other FMPs for other U.S. fisheries have typically gone a step further and specified a numeric value for the MSST. Under the BSAI and GOA Groundfish FMPs, the process of conducting an annual (or bi-annual) test involving the stock's size relative to B_{MSY} and ½ B_{MSY} and its ability to rebuild to B_{MSY} in 10 years if fished at F_{OFL} makes it impossible to tell *how close* a stock is to being overfished, and impossible to compare performance in this respect to that of other fisheries. Struggles with the NMFS Office of Sustainable Fisheries and others occur nearly every year over how to report the "real" MSSTs for BSAI and GOA groundfish stocks, which consume considerable amounts of time.

The reasons why the FMPs currently do not specify a numeric value for MSST are as follow:

1. When Amendments 56/56 were approved without inclusion of an MSST and the Secretary's initial interpretation proved to be infeasible, it seemed that the only defensible procedure (i.e., the only procedure that would *not* involve creation of a new, non-established policy) to comply with the Guidelines' requirement for inclusion of an MSST was to use the definition contained in the Guidelines themselves, but this did not provide a mechanism for specifying a numeric value.

2. Development of Amendments 96(BSAI)/87(GOA) might have provided an opportunity to include a mechanism for specifying a numeric value, but the need to get these amendments developed and approved quickly limited their contents to clarification of existing procedures only.

3. For stocks that are assessed using age-structured models, it was recognized early on that there is no unique stock size at which rebuilding to B_{MSY} would be expected to occur in 10 years if the stock were to be fished at $F=F_{OFL}$ in each year (this would not be the case for stocks assessed using biomass dynamic models, where a unique stock size *does* exist). This is addressed below.

Non-uniqueness of the stock size at which rebuilding to B_{MSY} is expected in 10 years if $F=F_{OFL}$

The question of uniqueness was explored using a simple, age-structured model. To keep the parameterization simple, the conventional rule of thumb in which $F_{35\%}$ equals M (e.g., Clark 1991) was assumed. Main model features included the following:

1. Linear weight at age (as in Thompson 1992).
2. Infinite maximum age.
3. Constant M with respect to age and time.
4. Selectivity=1 at all ages above the age of maturity.
5. The fishery occurs instantaneously at the start of the year.
6. Knife-edge maturity at the maximum age consistent with the conventional rule of thumb setting $F_{35\%}$ equal to M (the *maximum* consistent age was chosen because forcing $F_{35\%}$ to equal M in this model constrains the feasible range for the age at maturity to values lower than those that might be expected (e.g., Clark 1991, Jensen 1996)).
7. The ratio of weight at the age of maturity to weight at age 0 was set at the value that sets $F_{35\%}$ equal to M.
8. The OFL control rule was the same as the current Tier 3 rule, but expressed as exploitation rate E (i.e., $E=1-\exp(-F)$), not instantaneous F.
9. Catch=OFL in all years.
10. Exploitation rate was set at a constant initial level E_{ini} in all years prior to year 1
11. Prior to year 1, recruitment followed a sine wave with given mean, coefficient of variation (CV), period, and offset t_0 (an example is shown in Figure 7; the offset determines the time when the sine wave first passes through the mean on the upswing); from year 1 onward, recruitment was held constant at the average of the sine wave.

Two values of recruitment CV were analyzed: 0 and 0.5. For the CV=0 case, the period and t_0 parameters were not applicable. Otherwise, the following factorial design of parameters was used (mean recruitment was not included in the factorial design because it cancels out):

- M = {0.05, 0.10}
- CV = {0, 0.5}
- period = {5, 10, 20, 40}
- t_0/period = {0, 0.2, 0.4, 0.6, 0.8}

This design resulted in a total of 1 CV=0 case and 20 CV=0.5 cases for each value of M, giving a grand total of 42 cases. For each case, the model was solved for the value of E_{ini} at which the stock would rebuild to $B_{35\%}$ in exactly 10 years. The results are summarized in Table 1.

The critical values of E_{ini} are shown in the next-to-rightmost column of Table 1 (cells are shaded so that, for a given M and CV=0.5, the highest values of E_{ini} are red and the lowest are green). The following results were obtained for each value of M: 1) E_{ini} values in the CV=0 case fell within the range of E_{ini} values among the CV=0.5 cases, 2) the highest and lowest values of E_{ini} were obtained among the period=40 cases, and 3) there was at least one case where E_{ini} was less than M.

Ratios of initial biomass (B_{ini}) to $B_{35\%}$ are shown in the right-most column of Table 1 (shading convention is the same as for the preceding column). Some of the trends parallel those for E_{ini}. Specifically, for each value of M: 1) ratios in the CV=0 case fell within the range of ratios among the CV=0.5 cases, and 2) the highest and lowest ratios were obtained among the period=40 cases (with one exception: for M=0.10, the ratio for the {period=10, t_0/period=0.2} case was slightly lower than the minimum ratio among the period=40 cases).

Most important, though, were the following two results:

1. For M=0.05, all cases resulted in $B_{ini}/B_{35\%}$ ratios between 0.5 and 1.0; while for M=0.10, 16 cases resulted in ratios less than 0.5, and 5 cases resulted in ratios between 0.5 and 1.0. If any of the M=0.05 stocks or any of the 5 M=0.10 stocks with ratios between 0.5 and 1.0 had been fished initially at rates higher than their respective E_{ini} values, they would *not* have rebuilt to B_{MSY} within 10 years if fished at F_{OFL}. This casts doubt on the conclusion reached by the SSC in April 1998 regarding the extent to which the existing OFL control rules would assure rebuilding to B_{MSY} within 10 years if the stock were fished at F_{OFL}.

2. The initial stock size at which rebuilding to B_{MSY} would occur within 10 years if the stock were fished at F_{OFL} is not unique. Rather, it depends on the age structure at the start of the 10-year period. Among the M=0.05 cases, B_{ini} ranged from 79% to 97% of $B_{35\%}$. For M=0.10, 16 cases had B_{ini} values that were less than 50% of B_{MSY}, in which case MSST would bet set to ½ B_{MSY}, while the other 5 cases had B_{ini} values ranging from 53% to 63% of $B_{35\%}$.

<u>Some options for future consideration</u>

Some options for further analysis regarding issue #2, in addition to retaining the status quo, include the following:

1. Specify MSST as the greater of: a) ½ B_{MSY}, or b) the smallest *equilibrium* stock size at which the stock would be expected to rebuild to B_{MSY} within 10 years if it were fished at F_{OFL} in each year. Advantages: fairly simple; proximity of the stock to MSST could be measured; management of BSAI and GOA groundfish would be more comparable to other U.S. fisheries; may provide additional protection for long-lived stocks. Disadvantages: depending on the age structure of the stock, could result in a stock being declared "overfished" even though the stock would be expected to rebuild to B_{MSY} within 10 years when fished at F_{OFL}.

2. Specify MSST as the greater of: a) ½ B_{MSY}, or b) the smallest *disequilibrium* stock size at which the stock would be expected to rebuild to B_{MSY} within 10 years if it were fished at F_{OFL} in each year. Advantages: proximity of the stock to MSST could be measured; management of BSAI and GOA groundfish would be more comparable to other U.S. fisheries; may provide additional

protection for long-lived stocks; regardless of the age structure of the stock, would never result in a stock being declared “overfished” if the stock would be expected to rebuild to B_{MSY} within 10 years when fished at F_{OFL}. Disadvantages: very complicated; depending on the age structure of the stock, could result in a stock being declared “*not* overfished” even though the stock would *not* be expected to rebuild to B_{MSY} within 10 years when fished at F_{OFL}.

Issue #3: Possible ambiguities regarding how various anthropogenic removals should be A) treated in computation of fishing mortality reference points and B) counted against harvest specifications

Note: The term “anthropogenic removals” is intended to include removals resulting from scientific research. This somewhat awkward term is used rather than the more familiar “fishery removals” or “removals due to fishing” because the Magnuson-Stevens Act’s defines “fishing” as being exclusive of “any scientific research activity which is conducted by a scientific research vessel” (§3(16)). Also, “removals” should be understood here to mean “permanent removals from the *population*,” not just “permanent removals from the *ocean*” (e.g., fish discarded back into the ocean still count as “removals”).

Some potentially relevant excerpts from the National Standard Guidelines

In the following, page numbers refer to the page of the Federal Register notice in which the current version of the guidelines for National Standard 1 were published (Vol. 74, No. 11; January 16, 2009).

p. 3190: *Comment 35*: Several commenters suggested that NMFS clarify language to ensure that all aspects of fishing mortality (e.g., dead discards and postrelease mortality) are accounted for in the estimates of ABC or when setting the ACL, and that all catch is counted against OY…. *Response*: NMFS agrees that all sources of fishing mortality, including dead discards and post-release mortality from recreational fisheries must be accounted for, but believes that language in § 600.310(e)(3)(v)(C), (f)(2)(i) and (f)(3)(i) in both the proposed and final action sufficiently explains that catch includes fish that are retained for any purposes, mortality of fish that have been discarded, allocations for scientific research, and mortality from any other fishing activity.…

p. 3206: (e)(2)(ii)(A)(2) *Catch exceeds the OFL.* Should the annual catch exceed the annual OFL for 1 year or more, the stock or stock complex is considered subject to overfishing.

p. 3208: §600.310(e)(3)(v)(C) All catch must be counted against OY, including that resulting from bycatch, scientific research, and all fishing activities.

p. 3208: §600.310(f)(2)(i) *Catch* is the total quantity of fish, measured in weight or numbers of fish, taken in commercial, recreational, subsistence, tribal, and other fisheries. Catch includes fish that are retained for any purpose, as well as mortality of fish that are discarded.

p. 3209: §600.310(f)(3)(i) *Expression of ABC.* ABC should be expressed in terms of catch, but may be expressed in terms of landings as long as estimates of bycatch and any other fishing mortality not accounted for in the landings are incorporated into the determination of ABC.

p. 3210: §600.310(g)(2) *Inseason AMs.* Whenever possible, FMPs should include inseason monitoring and management measures to prevent catch from exceeding ACLs….

p. 3210: §600.310(g)(3) …If catch exceeds the ACL for a given stock or stock complex more than once in the last four years, the system of ACLs and AMs should be re-evaluated, and modified if necessary, to improve its performance and effectiveness….

p. 3213: §600.310(l)(5) *National Standard 9 (see §600.350).* Evaluation of stock status with respect to reference points must take into account mortality caused by bycatch. In addition, the estimation of catch should include the mortality of fish that are discarded.

Background and current FMP text

<u>Background</u>

September 2010: Final EA for Amendments 96(BSAI)/87(GOA) published. Under the heading "Total Catch Accounting," the EA reads as follows: "Regulations at 50 CFR §600.310(e)(3)(v)(C) require that 'all catch must be counted against OY, including that resulting from bycatch, scientific research, and all fishing activities.' The Groundfish FMPs would be amended to include the accounting for all commercial and research catch in the annual stock assessment process. All types of catch, including bait, state waters, and research catch (scientific research permits, letters of acknowledgement and exempted fishing permits), are estimated each year and provided to the stock assessment authors for inclusion in stock assessment models for recommending OFLs and ABCs for the following year. This will ensure that all catch is accounted for in the stock assessment process and results in OFLs and ABCs that take into account all types of harvests."

<u>Current FMP text</u>

Stock Assessment and Fishery Evaluation Report:

Scientists from the Alaska Fisheries Science Center, the Alaska Department of Fish and Game, other agencies, and universities prepare a Stock Assessment and Fishery Evaluation (SAFE) report annually. The SAFE report is scientifically based, citing data sources and interpretations. The SAFE report provides information to the Council for determining annual harvest specifications, documenting significant trends or changes in the stocks, marine ecosystem, and fisheries over time; and assessing the relative success of existing State and Federal fishery management programs. This document is reviewed first by the Groundfish Plan Team, then by the SSC and AP, and then by the Council. The review by the SSC constitutes the official scientific review for purposes of the Information Quality Act. Upon review and acceptance by the SSC, the SAFE report and any associated SSC comments constitute the best scientific information available for purposes of the Magnuson-Stevens Act.

The SAFE report consists of three volumes: a volume containing stock assessments, a volume containing economic analysis, and a volume describing ecosystem considerations.

The stock assessment volume contains a chapter or sub-chapter for each stock or stock complex in the "target species" category, and a summary chapter prepared by the Groundfish Plan Team. To the extent practicable, each chapter contains estimates of all annual harvest specifications except TAC, all reference points needed to compute such estimates, and all information needed to make annual status determinations with respect to "overfishing" and "overfished." In providing this information, the SAFE report uses the official time series of historic catch for each stock or stock complex. This time series, which is provided by the NMFS Alaska Region, includes estimates of retained and discarded catch taken in the groundfish fisheries; bycatch taken in other fisheries; state commercial, recreational, and subsistence fisheries; catches taken during scientific research; and catches taken during the prosecution of exempted fisheries.

The other two volumes contain additional economic, social, community, essential fish habitat, and ecological information pertinent to the success of management or the achievement of FMP objectives.

Harvest Specifications and TAC Overage:

Any amount of harvest that may exceed the TAC will be included in the total catch estimate used in the next stock assessment. A higher catch during a year will result in a lower biomass in the subsequent year. For stocks managed under Tiers 1-5, this would result in a lower maxABC in the subsequent year, all else being equal, because maxABC tends to vary directly with biomass (as a first approximation, maxABC = maxFABC x biomass; therefore a lower biomass results in a lower maxABC). For the special case of a stock managed under sub-tier "b" of any Tier 1-3 where spawning biomass is below the reference level (Bmsy in Tiers 1-2, B40% in Tier 3) of the ABC control rule, the decrease will be compounded because maxFABC also tends to vary directly with biomass (using the same first approximation, lower maxFABC and lower biomass results in an even lower maxABC). For Tier 6 stocks, the information used to establish harvest levels is insufficient to discern the existence or extent of biological consequences caused by an overage in the preceding year. The assessment for certain Tier 6 stocks may not be able to describe the biological consequences to the stock resulting from an overage. Consequently, the subsequent year's maxABC will not necessarily decrease. However, the SSC may recommend a decrease in the ABC for a Tier 6 stock.

Analysis

<u>Initial thoughts</u>

Two sub-issues are contained in Issue #3: A) How should anthropogenic removals from various sources be treated in the computation of fishing mortality reference points such as F_{MSY}, $F_{35\%}$, and $F_{40\%}$? B) *Which* anthropogenic removals should be counted against *which* harvest specifications?

With respect to the first sub-issue, the following are some possibilities for computing F_{MSY} (these presume the existence of multiple sources of removals, each with its own F, including those sources whose removals are discarded):

1. F_{MSY} is the vector of source-specific mortality rates that maximizes the aggregate equilibrium removals of the stock from all sources.
2. F_{MSY} is the vector of source-specific mortality rates that maximizes the aggregate equilibrium *landed* removals of the stock from all sources conditional on the existing Fs for the sources generating *discarded* removals.
3. F_{MSY} is the vector of source-specific mortality rates that maximizes the aggregate equilibrium *landed* removals of the stock from all sources conditional on F=0 for each of the sources generating *discarded* removals.
4. F_{MSY} is the mortality rate that maximizes equilibrium *total* removals of the stock from the groundfish fishery conditional on the existing Fs for the other sources of removals.
5. F_{MSY} is the mortality rate that maximizes equilibrium *total* removals of the stock from the groundfish fishery conditional on F=0 for each of the other sources of removals.

Analogous lists could be developed for $F_{35\%}$ and $F_{40\%}$. It may be noted that the original papers by Clark (1991, 1993) seemed to presume a single source of anthropogenic removals, viz., the target fishery. It is not clear how the results of those papers might have changed had additional sources of removals been included in the analysis. Because of this, it is probably premature to suggest that, even in the presence of multiple significant sources of removals, allowing the target fishery to fish at the $F_{35\%}$ rate will always tend in the long run to provide an average yield close to MSY.

Turning to the second sub-issue, here are some possibilities for the types of removals that should be counted against one or more of the various harvest specifications (TAC, ABC(=ACL), OFL, OY):

1. Catches taken in the groundfish fishery only.
2. Groundfish catches plus catches retained for sale in other fisheries.
3. Groundfish catches plus all catches taken in other fisheries (including discards and fish retained for use as bait).
4. Catches taken in all fisheries plus removals resulting from scientific research.

<u>Modeling the problem</u>

The two sub-issues may not be independent, of course. Therefore, they will be addressed simultaneously here using a simple, age-structured model broadly similar to the model analyzed under Issue #2. The major difference is that the model used here included two fisheries: a "target" fishery (fishery 1, with fishing mortality rate F_1 and catch C_1) and a "non-target" fishery (fishery 2, with fishing mortality rate F_2 and catch C_2). Other main model features included the following:

Features 1-4 were the same as in the model analyzed under Issue #2:

1. Linear weight at age.
2. Infinite maximum age.
3. Age-invariant M.
4. Selectivity=1 at all ages above the age of maturity.

Features 5-7 in the model analyzed under Issue #2 were modified in light of the addition of a non-target fishery as follows (bold italic font indicates a change from the previous model):

5. The ***target*** fishery occurs instantaneously at the start of the year; ***fishery 2 occurs at a constant rate throughout the year***.
6. Knife-edge maturity at the maximum age consistent with the conventional rule of thumb setting $F_{35\%}$ ***for the target fishery*** equal to M, ***given a zero rate of fishing mortality for fishery 2***.
7. The ratio of weight at the age of maturity to weight at age 0 was set at the value that sets $F_{35\%}$ ***for the target fishery*** equal to M, ***given a zero rate of fishing mortality for the fishery 2***.

Features 8-11 in the model analyzed under Issue #2 were replaced by the following

8. The stock-recruitment relationship follows the form suggested by Cushing (1971).
9. The Cushing exponent was set at the value that set F_{MSY} for the target fishery equal to M, given a zero rate of fishing mortality for fishery 2.
10. No kinks in the control rules for Tiers 2 and 3 (i.e., control rules are of the "constant F" form).
11. ABC=maxABC in all cases.

Figure 8 (based on M=0.05) shows an example of how equilibrium yield in this model varies for fishery 1, fishery 2, and the combined fisheries; each as a function of F_1. Equilibrium yield for the combined fisheries when F_2=0.5M is shown by the magenta curve, and is maximized at F_1=0.026, as indicated by the dashed magenta line. Equilibrium yield for fishery 1 when F_2=0 (same as equilibrium yield for the combined fisheries when F_2=0) is shown by the blue curve, and is maximized at F_1=0.05, as indicated by the blue dashed line. Equilibrium yield for fishery 1 when F_2=0.5M is shown by the red curve, and is maximized at F_1=0.091, as shown by the red dashed line. Equilibrium yield for fishery 2 given F_2=0.05 is shown by the green curve, and is maximized at F_1=0.

As can be inferred from Figure 8, one property of this model is that the value of F_1 that maximizes equilibrium yield from either fishery 1 or the combined fisheries is a function of F_2. Likewise, the value of F_1 that achieves a specified equilibrium level of relative spawning per recruit (e.g., 35%, 40%) is a function of F_2. To keep these properties explicit, the value of F_1 that maximizes the equilibrium yield from fishery 1 will be written $Fmsy_1(F_2)$, and the value of F_1 that achieves an equilibrium relative spawning per recruit level of X% will be written $Fspr_1(F_2\text{,X\%})$. An example is illustrated in Figure 9 (based on M=0.05). Both $Fmsy_1(F_2)$ and $Fspr_1(F_2\text{,35\%})$ are expressed relative to M. As the figure shows, these two fishing mortality reference points move in opposite directions as functions of F_2, with $Fmsy_1(F_2)$ increasing (blue curve) and $Fspr_1(F_2\text{,35\%})$ decreasing (red line) until it reaches zero at $F_2=M$.

The model was run for 320 different cases, using the following factorial design:

- M = {0.05, 0.10, 0.20, 0.30}
- F_2/M = {0.1, 0.2, 0.3, 0.4, 0.5}
- Tier = {2, 3}
- Computation of $Fabc_1$ and $Fofl_1$ = {two *tier-specific* choices described below}
- Computation of C_1 and C_2 = {two *tier-specific* choices described below}
- Computation of ABC and OFL = {two *non-tier-specific* choices described below}

For the Tier 2 cases, the choices for computation of $Fabc_1$, $Fofl_1$, C_1, and C_2 were as follow:

$Fabc_1$ and $Fofl_1$ were computed using either

$$Fabc_1 = \left(\frac{Fspr_1(0,40\%)}{Fspr_1(0,35\%)}\right)\cdot Fmsy_1(0) \quad \text{and} \quad Fofl_1 = Fmsy_1(0) \quad , \quad \text{or}$$

$$Fabc_1 = \left(\frac{Fspr_1(0,40\%)}{Fspr_1(0,35\%)}\right)\cdot Fmsy_1(F_2) \quad \text{and} \quad Fofl_1 = Fmsy_1(F_2) \quad .$$

C_1 and C_2 were computed using either

$$F_1 = \left(\frac{Fspr_1(0,40\%)}{Fspr_1(0,35\%)}\right)\cdot Fmsy_1(0) \quad \text{and} \quad F_2 = F_2 \quad , \quad \text{or}$$

$$F_1 = \left(\frac{Fspr_1(0,40\%)}{Fspr_1(0,35\%)}\right)\cdot Fmsy_1(F_2) \quad \text{and} \quad F_2 = F_2 \quad .$$

For the Tier 3 cases, the choices for computation of $Fabc_1$, $Fofl_1$, C_1, and C_2 were as follow:

$Fabc_1$ and $Fofl_1$ were computed using either

$$Fabc_1 = Fspr_1(0,40\%) \quad \text{and} \quad Fofl_1 = Fspr_1(0,35\%) \quad , \quad \text{or}$$
$$Fabc_1 = Fspr_1(F_2,40\%) \quad \text{and} \quad Fofl_1 = Fspr_1(F_2,35\%) \quad .$$

C_1 and C_2 were computed using either

$F_1 = Fspr_1(0, 40\%)$ and $F_2 = F_2$, *or*
$F_1 = Fspr_1(F_2, 40\%)$ and $F_2 = F_2$.

For the Tier 2 and Tier 3 cases, the choices for computation of ABC and OFL were as follow:

ABC and OFL were computed using $Fabc_1$ only (for ABC) and $Fofl_1$ only (for OFL), or
ABC and OFL were computed using $Fabc_1$ and F_2 (for ABC) and $Fofl_1$ and F_2 (for OFL).

The results are shown in Table 2 (eight pages). Here is how to interpret these tables:

1. In the third column, "F_1 assumes F_2=0?" refers to whether F_2 was assumed to equal zero when determining the value of F_1 that went into the computation of C_1 and C_2.
2. In the fourth column, "F_1 assumes F_2=0?" refers to whether F_2 was assumed to equal zero when determining the values of $Fabc_1$ and $Fofl_1$ that went into the computation of ABC and OFL.
3. "Specs exclude C_2?" refers to whether ABC and OFL were computed with C_2 excluded.
4. For the Tier 2 tables, color coding in the first group of four colored columns indicates how close the cell values are to unity (i.e., how close the sustainable yield under the ABC or OFL control rules is to MSY). Green = closest to unity, grading to red = farthest from unity.
5. For the Tier 3 tables, color coding in the first group of four colored columns indicates how close the cell values are to the intended relative spawning per recruit (RSPR) values. In the "ABC RSPR" columns, green = closest to 0.40, grading to red = farthest from 0.40; in the "OFL RSPR" columns, green = closest to 0.35, grading to red = farthest from 0.35.
6. For all tables, color coding in the second group of four colored columns indicates cell values relative to zero. Red = cell value greater than zero (catch exceeds ABC or OFL), yellow = cell value equal to zero (catch equals ABC or OFL), green = cell value less than zero (catch is less than ABC or OFL). For both ABC and OFL, two columns are shown. The first shows the result if both C_1 and C_2 are counted against the respective specification, and the second shows the result when only C_1 is counted.

The values listed in Table 2 cover wide ranges, but some trends are evident. One of these is that, for all values of *M* and both Tiers, the highest and lowest values in columns 6-9 occur when F_2 is highest (bottom section on each page of each table), with low values occurring when F_2 is assumed to be zero, both when determining the value of F_1 that went into the computation of C_1 and C_2 and when determining the values of $Fabc_1$ and $Fofl_1$ that went into the computation of ABC and OFL. In other words, equilibrium yields and relative spawning per recruit are lowest and when F_2 is high and ignored.

The cases where catch equaled ABC exactly are the same on all pages of Table 2. These are basically tautologies, and have no relationship to how close equilibrium yields are to MSY (Tier 2) or how well specified levels of relative spawning per recruit are achieved (Tier 3).

There were many cases where ABC or OFL was exceeded. Several of these corresponded to situations in which C_2 was ignored when setting the harvest specifications but then counted against those specifications after the fact, which is a fairly predictable result. However, there were not the *only* cases where overages occurred. Even when only C_1 was counted against the harvest specification, there were many cases where overages occurred, with respect to both ABC and OFL. In cases where only C_1 was counted against OFL, consistent patterns emerged for both Tier 2 and Tier 3. For Tier 2, an overage occurred whenever columns 3, 4, and 5 equaled "no," "yes," and "yes," respectively and F_2 was at least 20% of *M*. For Tier 3, an overage occurred whenever columns 3, 4, and 5 equaled "yes," "no," and "yes," respectively and F_2 was at least 20% of *M*.

<u>Some options for future consideration</u>

Some options for further analysis regarding issue #3, in addition to retaining the status quo, include the following:

1. Clarify how fishing mortality reference points should be computed when multiple sources of significant anthropogenic removals exist. Advantage: should reduce the possibility of misusing existing reference points. Disadvantage: may complicate the management process.

2. Clarify which anthropogenic removals should be counted against the various harvest specifications. Advantages: compliance with National Standard 1 Guidelines would be more obvious than at present. Disadvantages: knowing which removals should be counted against the specifications, by itself, does nothing to prevent those specifications from being exceeded; may complicate the management process.

3. Set TAC below ABC by an amount sufficient to keep total anthropogenic removals below ABC. Advantages: compliance with the National Standard 1 Guidelines would be more obvious than at present; total anthropogenic removals would likely not exceed ABC. Disadvantages: fewer fish would be available to the groundfish fishery; would almost certainly complicate the management process, including the setting of TACs and the authorization of research fishing.

4. Redefine ABC or ACL to be exclusive of certain types of anthropogenic removals. Advantages: might not require reductions in TAC in order to keep ABC/ACL from being exceeded (because some removals would not count). Disadvantages: total anthropogenic removals might still exceed OY or OFL (because the removals excluded from ABC/ACL would not be excluded from OY/OFL); compliance with the National Standard 1 Guidelines might not be obvious.

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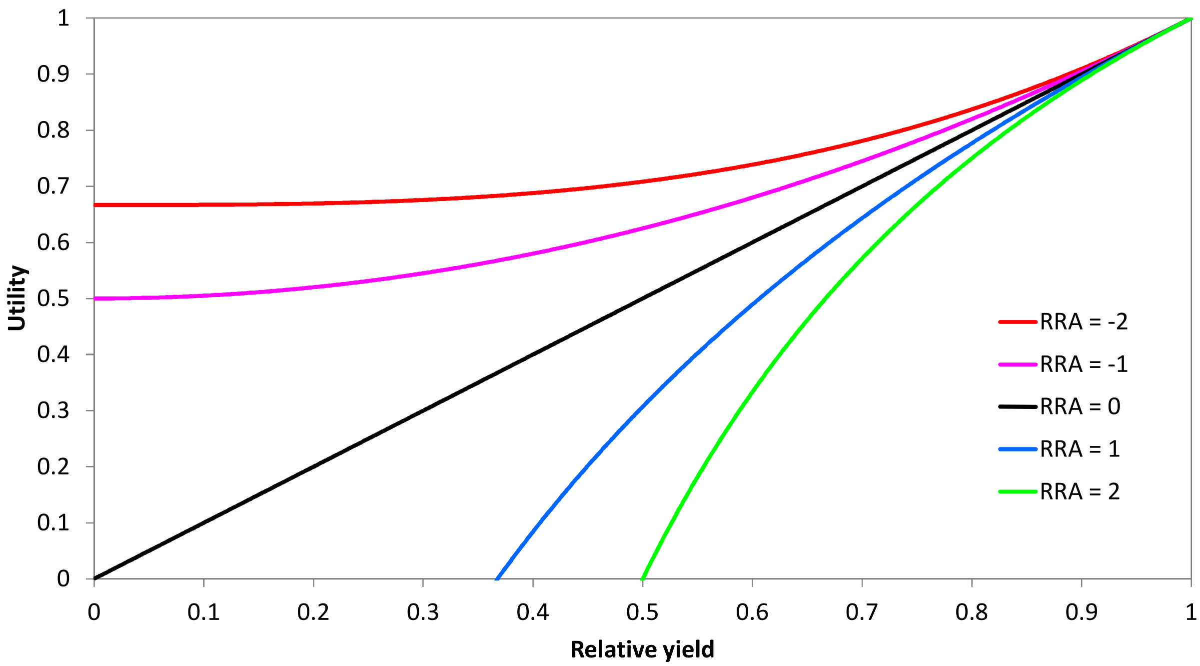


Figure 1. Five utility functions exhibiting constant relative risk aversion (*RRA*).

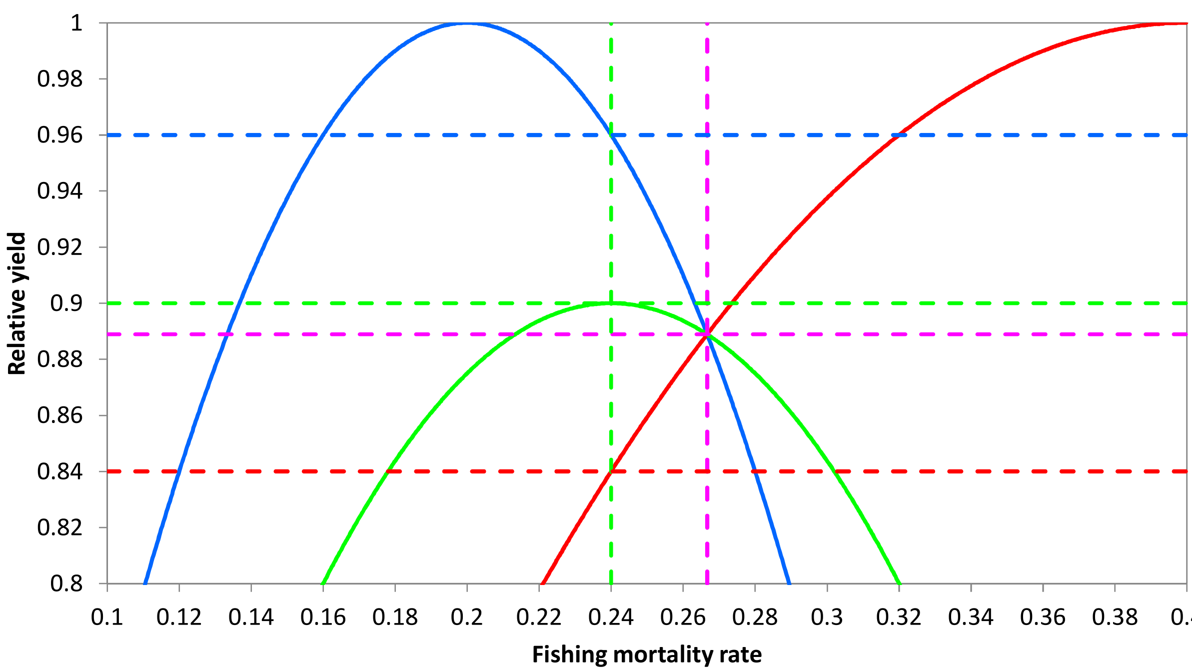


Figure 2. Relative yield (*RY*) from a Schaefer model under *Fmsy*=0.2 (blue curve) and *Fmsy*=0.4 (red curve). Average *RY* is shown by the green curve. The intersection of the blue and red curves is indicated by the dashed magenta lines. Maximum average *RY* is indicated by the green dashed lines. Blue and red dashed lines indicate *RY* from the blue and red curves when *F* is at the value that maximizes average *RY*.

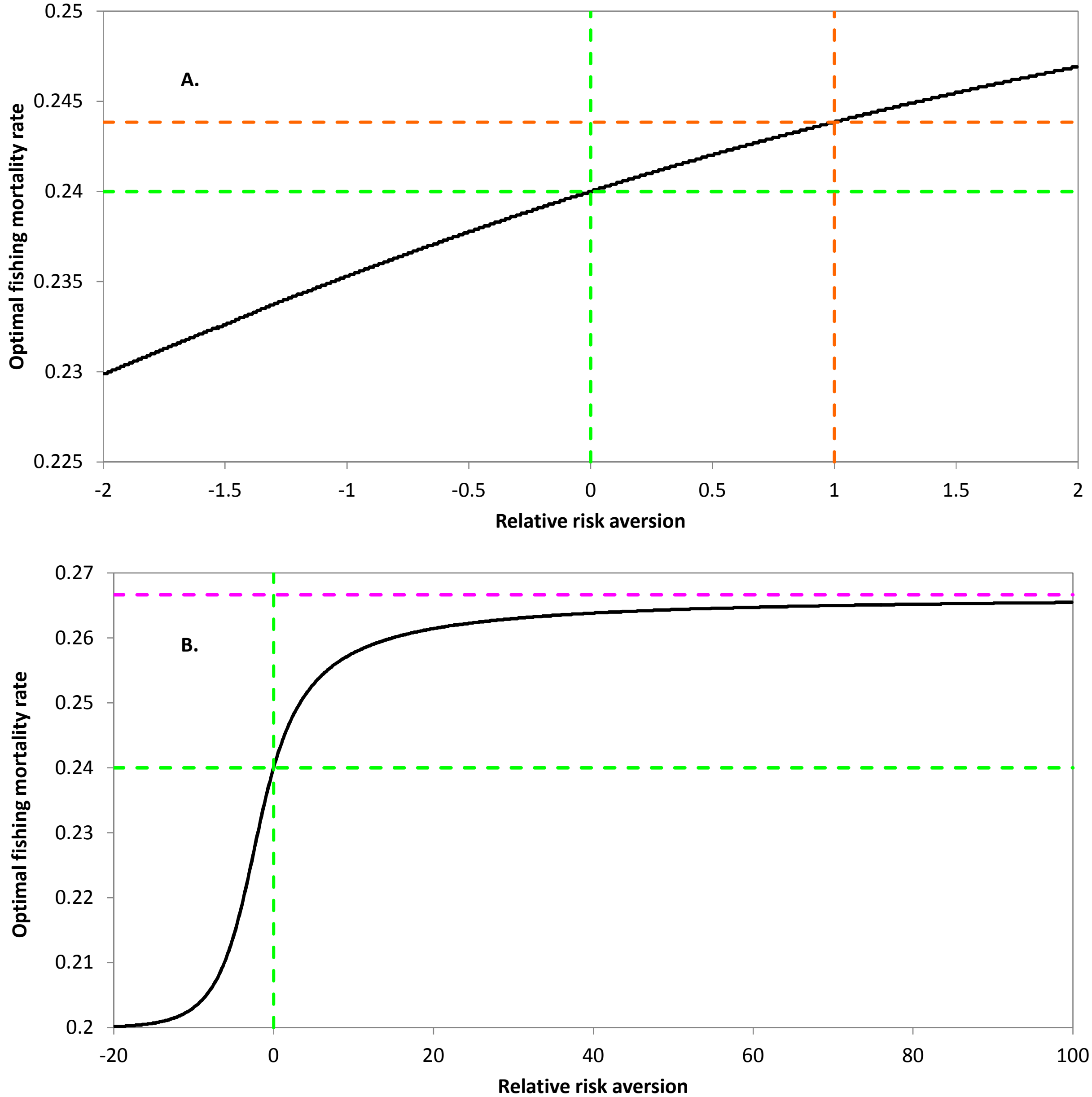


Figure 3. Optimal fishing mortality rates for the Schaefer model under equi-probable *Fmsy* values of 0.2 and 0.4 as a function of the level of relative risk aversion (*RRA*). In both panels, the black curve indicates the optimal fishing mortality rate across the respective range of RRA values, and the dashed green lines indicate the location of the risk-neutral optimum. Figure 3a: *RRA* ranges from -2 to 2. Dashed orange lines indicate location of the optimum when *RRA*=1. Figure 3b: *RRA* ranges from -20 to 100 (note that the range showed in Figure 3a is a subset of the range shown in Figure 3b). Dashed magenta line indicates location of F_{int}, the value of F at which the two relative yield curves in Figure 2 intersect.

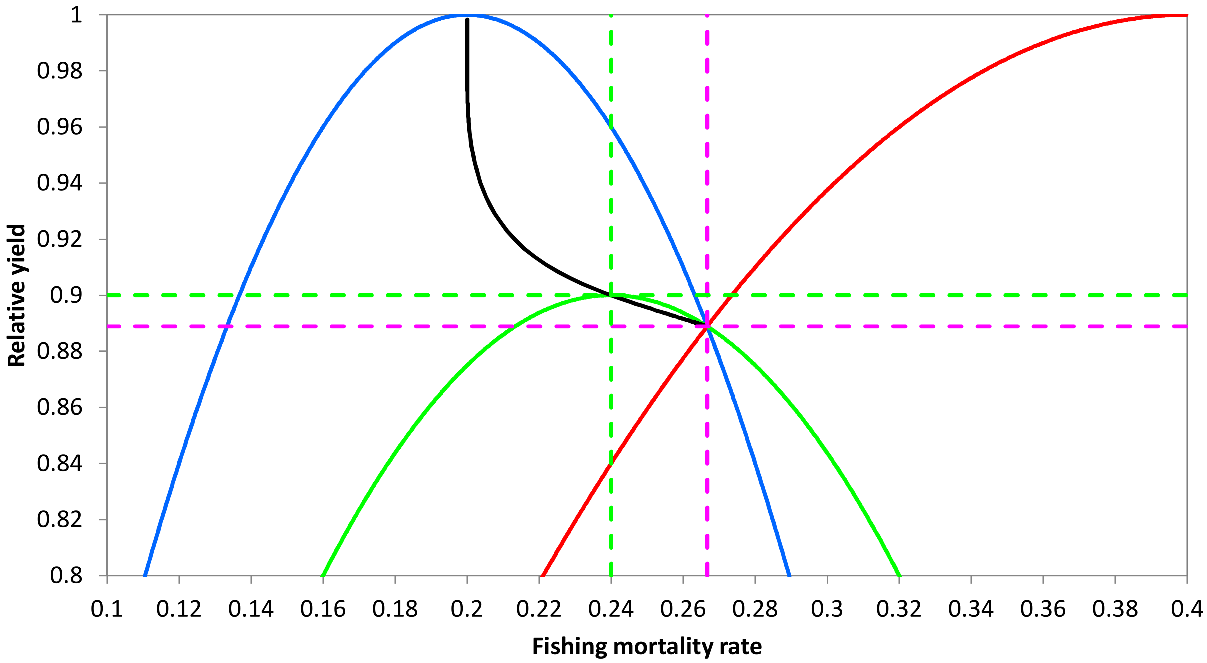


Figure 4. Same as Figure 2, but with dashed red and blue lines omitted, and locus of optima added (black curve). Optima correspond to a continuous range of *RRA* values from $-\infty$ to ∞.

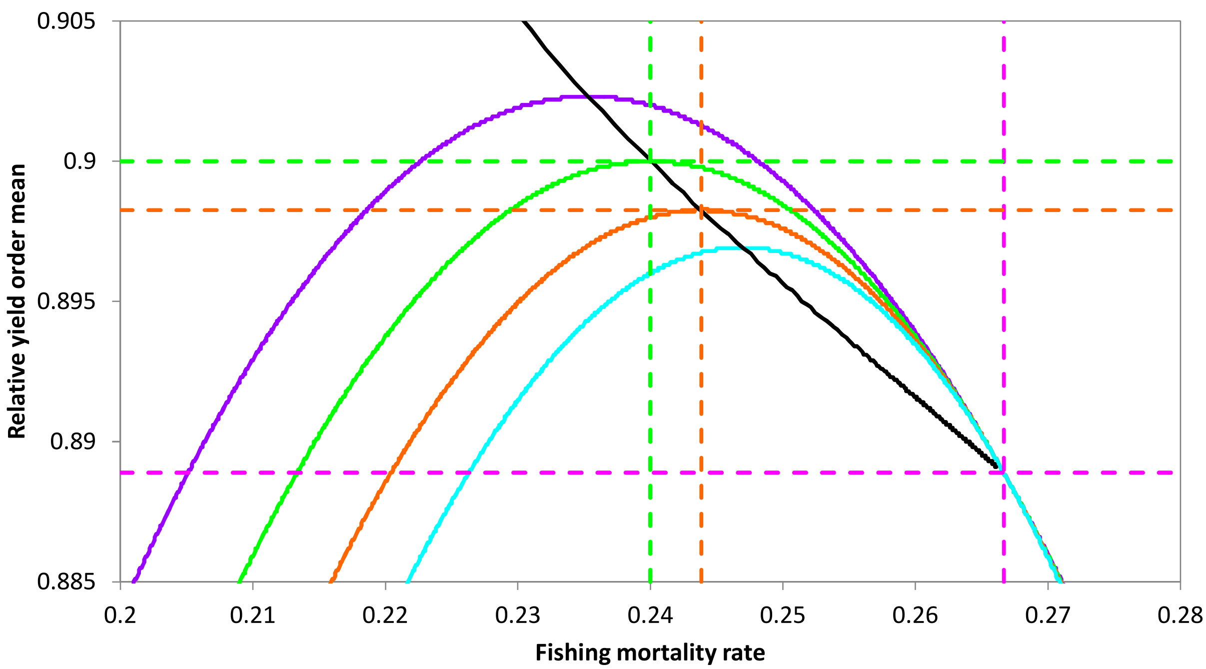


Figure 5. Order means of relative yield (*RY*) as a function of the fishing mortality rate, for four values of relative risk aversion (*RRA*): -1 (purple), 0 (green), 1 (orange), and 2 (light blue). See text for details.

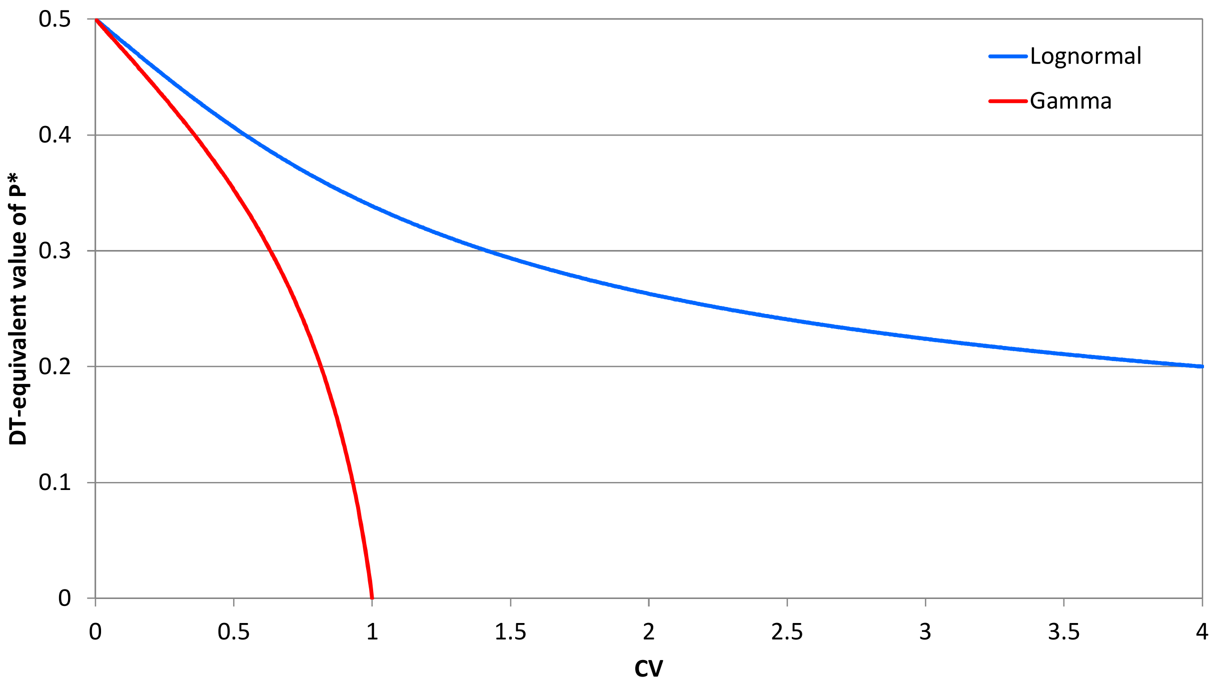


Figure 6. Values of P^* that set $maxF_{ABC}$ (as determined by the P^* approach) equal to the harmonic mean of *Fmsy*, for two functional forms (lognormal and gamma) of the *Fmsy* pdf and a range of values for the coefficient of variation characterizing those pdfs. The harmonic mean is the decision-theoretic optimum.

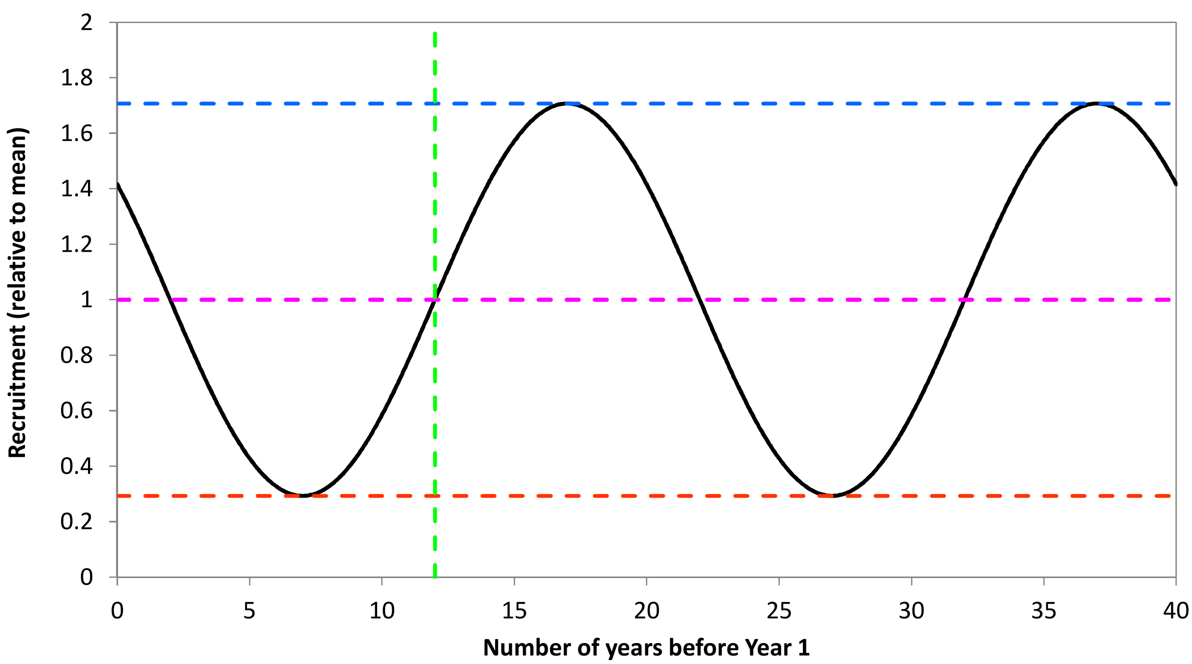


Figure 7. Example relative recruitment trend (black curve). Blue and red dashed lines indicate maxima and minima (displaced from unity by sqrt(2)CV). Dashed green line indicates the "offset" (i.e., the time at which the curve first passes through unity (dashed magenta line) on the upswing).

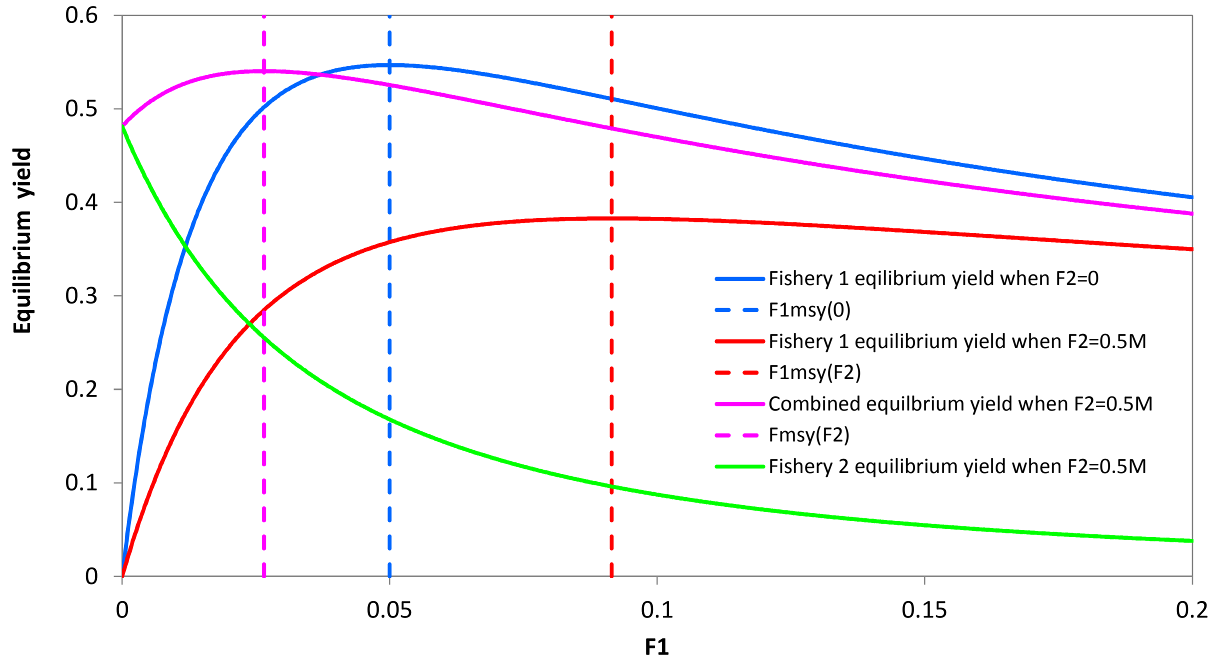


Figure 8. Equilibrium yield for fishery 1, fishery 2, and the combined fisheries as a function of F_1, based on M=0.05. Equilibrium yield for fishery 1 is shown for two values of F_2 (0 and 0.5M). Equilibrium yield for the combined fisheries and fishery 2 are conditional on F_2=0.5M.

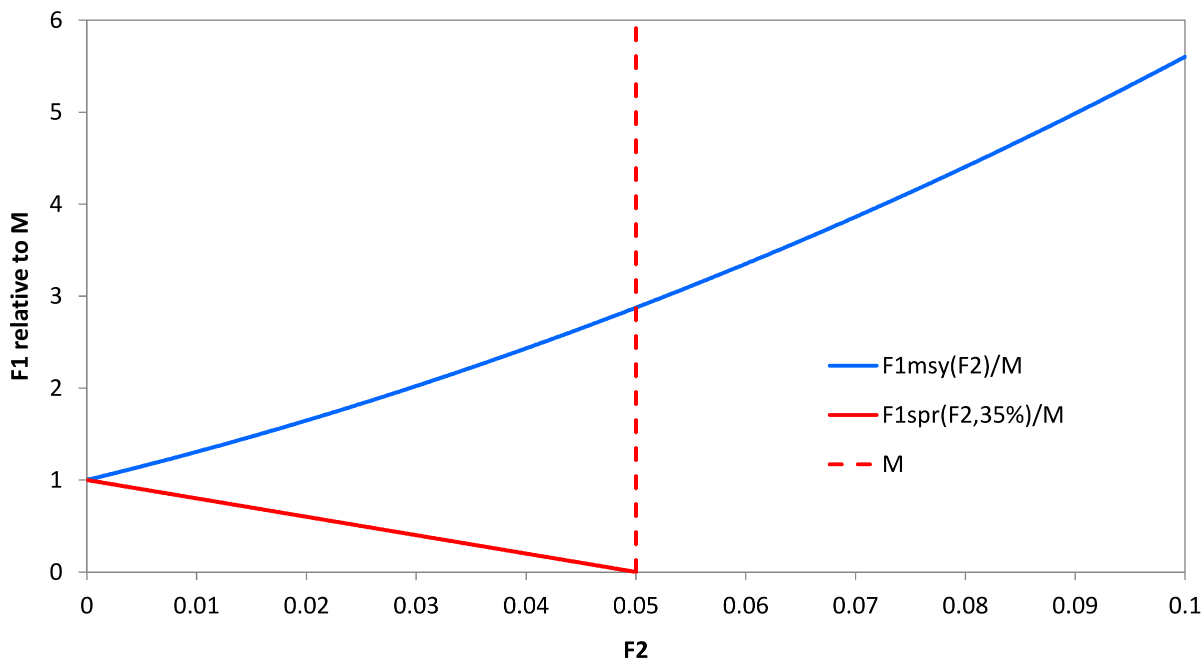


Figure 9. Values of F_1 that maximize equilibrium yield from fishery 1 (blue curve) and that set equilibrium spawning per recruit equal to 35% of the pristine value (red line) as a function of F_2 (based on M=0.05). Values of F_1 are expressed relative to M.

Table 1. Minimum initial biomass (relative to $B_{35\%}$) at which rebuilding to $B_{35\%}$ will be achieved within 10 years if the stock is fished at F_{OFL} every year under a variety of scenarios. See main text for details.

M	Rec. CV	Period	t_0/Per.	E_{ini}	$B_{ini}/B_{35\%}$
0.05	0	n/a	n/a	0.059	0.867
0.05	0.5	5	0	0.060	0.863
0.05	0.5	5	0.2	0.063	0.850
0.05	0.5	5	0.4	0.060	0.860
0.05	0.5	5	0.6	0.056	0.879
0.05	0.5	5	0.8	0.056	0.881
0.05	0.5	10	0	0.054	0.891
0.05	0.5	10	0.2	0.063	0.856
0.05	0.5	10	0.4	0.068	0.836
0.05	0.5	10	0.6	0.060	0.859
0.05	0.5	10	0.8	0.052	0.894
0.05	0.5	20	0	0.078	0.814
0.05	0.5	20	0.2	0.060	0.848
0.05	0.5	20	0.4	0.046	0.916
0.05	0.5	20	0.6	0.050	0.914
0.05	0.5	20	0.8	0.068	0.853
0.05	0.5	40	0	0.053	0.921
0.05	0.5	40	0.2	0.087	0.830
0.05	0.5	40	0.4	0.090	0.795
0.05	0.5	40	0.6	0.047	0.871
0.05	0.5	40	0.8	0.036	0.970
0.10	0	n/a	n/a	0.242	0.441
0.10	0.5	5	0	0.205	0.472
0.10	0.5	5	0.2	0.194	0.492
0.10	0.5	5	0.4	0.248	0.444
0.10	0.5	5	0.6	0.321	0.400
0.10	0.5	5	0.8	0.282	0.410
0.10	0.5	10	0	0.324	0.414
0.10	0.5	10	0.2	0.390	0.381
0.10	0.5	10	0.4	0.225	0.435
0.10	0.5	10	0.6	0.159	0.533
0.10	0.5	10	0.8	0.202	0.495
0.10	0.5	20	0	0.147	0.573
0.10	0.5	20	0.2	0.279	0.450
0.10	0.5	20	0.4	0.434	0.388
0.10	0.5	20	0.6	0.333	0.389
0.10	0.5	20	0.8	0.127	0.549
0.10	0.5	40	0	0.081	0.633
0.10	0.5	40	0.2	0.142	0.572
0.10	0.5	40	0.4	0.327	0.424
0.10	0.5	40	0.6	0.461	0.383
0.10	0.5	40	0.8	0.277	0.407

Table 2 (p. 1 of 8: *M*=0.05, Tier 2). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 2							
					ABC SY/MSY		OFL SY/MSY		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.05	0.005	yes	yes	yes	0.977	0.977	0.996	0.996	0.116	0.000	-0.079	-0.175
0.05	0.005	yes	yes	no	0.977	0.977	0.996	0.996	0.000	-0.104	-0.159	-0.246
0.05	0.005	yes	no	yes	0.977	0.992	0.996	1.000	-0.025	-0.127	-0.195	-0.279
0.05	0.005	yes	no	no	0.977	0.992	0.996	1.000	-0.115	-0.207	-0.256	-0.334
0.05	0.005	no	yes	yes	0.992	0.977	1.000	0.996	0.260	0.145	0.040	-0.055
0.05	0.005	no	yes	no	0.992	0.977	1.000	0.996	0.129	0.026	-0.050	-0.137
0.05	0.005	no	no	yes	0.992	0.992	1.000	1.000	0.101	0.000	-0.091	-0.174
0.05	0.005	no	no	no	0.992	0.992	1.000	1.000	0.000	-0.091	-0.160	-0.237
0.05	0.01	yes	yes	yes	0.958	0.958	0.986	0.986	0.232	0.000	0.016	-0.175
0.05	0.01	yes	yes	no	0.958	0.958	0.986	0.986	0.000	-0.188	-0.146	-0.306
0.05	0.01	yes	no	yes	0.958	0.993	0.986	1.000	-0.051	-0.229	-0.216	-0.363
0.05	0.01	yes	no	no	0.958	0.993	0.986	1.000	-0.193	-0.345	-0.315	-0.443
0.05	0.01	no	yes	yes	0.993	0.958	1.000	0.986	0.526	0.298	0.260	0.071
0.05	0.01	no	yes	no	0.993	0.958	1.000	0.986	0.239	0.054	0.059	-0.100
0.05	0.01	no	no	yes	0.993	0.993	1.000	1.000	0.176	0.000	-0.028	-0.174
0.05	0.01	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.150	-0.150	-0.278
0.05	0.015	yes	yes	yes	0.935	0.935	0.972	0.972	0.346	0.000	0.111	-0.175
0.05	0.015	yes	yes	no	0.935	0.935	0.972	0.972	0.000	-0.257	-0.134	-0.357
0.05	0.015	yes	no	yes	0.935	0.993	0.972	1.000	-0.076	-0.314	-0.236	-0.433
0.05	0.015	yes	no	no	0.935	0.993	0.972	1.000	-0.251	-0.444	-0.358	-0.523
0.05	0.015	no	yes	yes	0.993	0.935	1.000	0.972	0.797	0.458	0.483	0.203
0.05	0.015	no	yes	no	0.993	0.935	1.000	0.972	0.335	0.083	0.156	-0.063
0.05	0.015	no	no	yes	0.993	0.993	1.000	1.000	0.233	0.000	0.020	-0.173
0.05	0.015	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.189	-0.143	-0.305
0.05	0.02	yes	yes	yes	0.911	0.911	0.954	0.954	0.461	0.000	0.205	-0.175
0.05	0.02	yes	yes	no	0.911	0.911	0.954	0.954	0.000	-0.315	-0.125	-0.401
0.05	0.02	yes	no	yes	0.911	0.993	0.954	1.000	-0.101	-0.385	-0.256	-0.491
0.05	0.02	yes	no	no	0.911	0.993	0.954	1.000	-0.296	-0.518	-0.393	-0.584
0.05	0.02	no	yes	yes	0.993	0.911	1.000	0.954	1.074	0.625	0.711	0.341
0.05	0.02	no	yes	no	0.993	0.911	1.000	0.954	0.420	0.113	0.243	-0.026
0.05	0.02	no	no	yes	0.993	0.993	1.000	1.000	0.276	0.000	0.056	-0.173
0.05	0.02	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.216	-0.138	-0.325
0.05	0.025	yes	yes	yes	0.885	0.885	0.934	0.934	0.574	0.000	0.299	-0.175
0.05	0.025	yes	yes	no	0.885	0.885	0.934	0.934	0.000	-0.365	-0.116	-0.439
0.05	0.025	yes	no	yes	0.885	0.993	0.934	1.000	-0.125	-0.444	-0.275	-0.540
0.05	0.025	yes	no	no	0.885	0.993	0.934	1.000	-0.331	-0.575	-0.421	-0.632
0.05	0.025	no	yes	yes	0.993	0.885	1.000	0.934	1.354	0.799	0.943	0.485
0.05	0.025	no	yes	no	0.993	0.885	1.000	0.934	0.495	0.143	0.322	0.010
0.05	0.025	no	no	yes	0.993	0.993	1.000	1.000	0.309	0.000	0.084	-0.172
0.05	0.025	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.236	-0.134	-0.338

Table 2 (p. 2 of 8: *M*=0.05, Tier 3). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 3							
					ABC RSPR		OFL RSPR		ABC overage		OFL overage	
M	F2	Catch	Specs		Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.05	0.005	yes	yes	yes	0.371	0.371	0.327	0.327	0.116	0.000	-0.079	-0.175
0.05	0.005	yes	yes	no	0.371	0.371	0.327	0.327	0.000	-0.104	-0.159	-0.246
0.05	0.005	yes	no	yes	0.371	0.400	0.327	0.350	0.268	0.136	0.021	-0.085
0.05	0.005	yes	no	no	0.371	0.400	0.327	0.350	0.119	0.003	-0.077	-0.173
0.05	0.005	no	yes	yes	0.400	0.371	0.350	0.327	-0.003	-0.120	-0.177	-0.273
0.05	0.005	no	yes	no	0.400	0.371	0.350	0.327	-0.107	-0.211	-0.249	-0.336
0.05	0.005	no	no	yes	0.400	0.400	0.350	0.350	0.132	0.000	-0.088	-0.195
0.05	0.005	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.117	-0.175	-0.272
0.05	0.01	yes	yes	yes	0.345	0.345	0.306	0.306	0.232	0.000	0.016	-0.175
0.05	0.01	yes	yes	no	0.345	0.345	0.306	0.306	0.000	-0.188	-0.146	-0.306
0.05	0.01	yes	no	yes	0.345	0.400	0.306	0.350	0.620	0.315	0.264	0.026
0.05	0.01	yes	no	no	0.345	0.400	0.306	0.350	0.239	0.006	0.021	-0.171
0.05	0.01	no	yes	yes	0.400	0.345	0.350	0.306	-0.006	-0.240	-0.180	-0.373
0.05	0.01	no	yes	no	0.400	0.345	0.350	0.306	-0.193	-0.383	-0.310	-0.472
0.05	0.01	no	no	yes	0.400	0.400	0.350	0.350	0.308	0.000	0.020	-0.220
0.05	0.01	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.235	-0.176	-0.370
0.05	0.015	yes	yes	yes	0.322	0.322	0.288	0.288	0.346	0.000	0.111	-0.175
0.05	0.015	yes	yes	no	0.322	0.322	0.288	0.288	0.000	-0.257	-0.134	-0.357
0.05	0.015	yes	no	yes	0.322	0.400	0.288	0.350	1.105	0.564	0.575	0.170
0.05	0.015	yes	no	no	0.322	0.400	0.288	0.350	0.358	0.009	0.119	-0.169
0.05	0.015	no	yes	yes	0.400	0.322	0.350	0.288	-0.009	-0.360	-0.182	-0.472
0.05	0.015	no	yes	no	0.400	0.322	0.350	0.288	-0.264	-0.525	-0.363	-0.589
0.05	0.015	no	no	yes	0.400	0.400	0.350	0.350	0.550	0.000	0.160	-0.252
0.05	0.015	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.355	-0.176	-0.468
0.05	0.02	yes	yes	yes	0.302	0.302	0.272	0.272	0.461	0.000	0.205	-0.175
0.05	0.02	yes	yes	no	0.302	0.302	0.272	0.272	0.000	-0.315	-0.125	-0.401
0.05	0.02	yes	no	yes	0.302	0.400	0.272	0.350	1.818	0.930	0.989	0.362
0.05	0.02	yes	no	no	0.302	0.400	0.272	0.350	0.478	0.012	0.217	-0.167
0.05	0.02	no	yes	yes	0.400	0.302	0.350	0.272	-0.012	-0.482	-0.185	-0.572
0.05	0.02	no	yes	no	0.400	0.302	0.350	0.272	-0.324	-0.645	-0.408	-0.689
0.05	0.02	no	no	yes	0.400	0.400	0.350	0.350	0.907	0.000	0.346	-0.294
0.05	0.02	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.476	-0.177	-0.568
0.05	0.025	yes	yes	yes	0.284	0.284	0.257	0.257	0.574	0.000	0.299	-0.175
0.05	0.025	yes	yes	no	0.284	0.284	0.257	0.257	0.000	-0.365	-0.116	-0.439
0.05	0.025	yes	no	yes	0.284	0.400	0.257	0.350	2.973	1.523	1.566	0.630
0.05	0.025	yes	no	no	0.284	0.400	0.257	0.350	0.598	0.015	0.315	-0.165
0.05	0.025	no	yes	yes	0.400	0.284	0.350	0.257	-0.015	-0.604	-0.187	-0.673
0.05	0.025	no	yes	no	0.400	0.284	0.350	0.257	-0.374	-0.748	-0.447	-0.778
0.05	0.025	no	no	yes	0.400	0.400	0.350	0.350	1.486	0.000	0.606	-0.354
0.05	0.025	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.598	-0.177	-0.669

Table 2 (p. 3 of 8: *M*=0.1, Tier 2). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 2							
					ABC SY/MSY		OFL SY/MSY		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.1	0.01	yes	yes	yes	0.977	0.977	0.996	0.996	0.111	0.000	-0.081	-0.172
0.1	0.01	yes	yes	no	0.977	0.977	0.996	0.996	0.000	-0.100	-0.157	-0.241
0.1	0.01	yes	no	yes	0.977	0.992	0.996	1.000	-0.029	-0.126	-0.195	-0.276
0.1	0.01	yes	no	no	0.977	0.992	0.996	1.000	-0.114	-0.202	-0.253	-0.328
0.1	0.01	no	yes	yes	0.992	0.977	1.000	0.996	0.254	0.144	0.037	-0.053
0.1	0.01	no	yes	no	0.992	0.977	1.000	0.996	0.129	0.030	-0.048	-0.131
0.1	0.01	no	no	yes	0.992	0.992	1.000	1.000	0.096	0.000	-0.092	-0.171
0.1	0.01	no	no	no	0.992	0.992	1.000	1.000	0.000	-0.087	-0.157	-0.231
0.1	0.02	yes	yes	yes	0.957	0.957	0.986	0.986	0.220	0.000	0.010	-0.172
0.1	0.02	yes	yes	no	0.957	0.957	0.986	0.986	0.000	-0.181	-0.143	-0.298
0.1	0.02	yes	no	yes	0.957	0.993	0.986	1.000	-0.058	-0.229	-0.219	-0.360
0.1	0.02	yes	no	no	0.957	0.993	0.986	1.000	-0.192	-0.338	-0.311	-0.436
0.1	0.02	no	yes	yes	0.993	0.957	1.000	0.986	0.511	0.296	0.251	0.073
0.1	0.02	no	yes	no	0.993	0.957	1.000	0.986	0.238	0.062	0.061	-0.090
0.1	0.02	no	no	yes	0.993	0.993	1.000	1.000	0.166	0.000	-0.033	-0.170
0.1	0.02	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.142	-0.147	-0.268
0.1	0.03	yes	yes	yes	0.934	0.934	0.971	0.971	0.329	0.000	0.100	-0.172
0.1	0.03	yes	yes	no	0.934	0.934	0.971	0.971	0.000	-0.248	-0.132	-0.347
0.1	0.03	yes	no	yes	0.934	0.993	0.971	1.000	-0.087	-0.313	-0.242	-0.429
0.1	0.03	yes	no	no	0.934	0.993	0.971	1.000	-0.250	-0.436	-0.355	-0.515
0.1	0.03	no	yes	yes	0.993	0.934	1.000	0.971	0.773	0.456	0.467	0.205
0.1	0.03	no	yes	no	0.993	0.934	1.000	0.971	0.334	0.096	0.157	-0.049
0.1	0.03	no	no	yes	0.993	0.993	1.000	1.000	0.217	0.000	0.012	-0.169
0.1	0.03	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.178	-0.140	-0.293
0.1	0.04	yes	yes	yes	0.909	0.909	0.953	0.953	0.437	0.000	0.189	-0.172
0.1	0.04	yes	yes	no	0.909	0.909	0.953	0.953	0.000	-0.304	-0.123	-0.389
0.1	0.04	yes	no	yes	0.909	0.993	0.953	1.000	-0.116	-0.384	-0.264	-0.488
0.1	0.04	yes	no	no	0.909	0.993	0.953	1.000	-0.295	-0.509	-0.389	-0.575
0.1	0.04	no	yes	yes	0.993	0.909	1.000	0.953	1.038	0.624	0.686	0.344
0.1	0.04	no	yes	no	0.993	0.909	1.000	0.953	0.418	0.131	0.245	-0.008
0.1	0.04	no	no	yes	0.993	0.993	1.000	1.000	0.254	0.000	0.044	-0.168
0.1	0.04	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.203	-0.134	-0.310
0.1	0.05	yes	yes	yes	0.883	0.883	0.932	0.932	0.543	0.000	0.277	-0.172
0.1	0.05	yes	yes	no	0.883	0.883	0.932	0.932	0.000	-0.352	-0.114	-0.426
0.1	0.05	yes	no	yes	0.883	0.993	0.932	1.000	-0.143	-0.445	-0.285	-0.537
0.1	0.05	yes	no	no	0.883	0.993	0.932	1.000	-0.331	-0.566	-0.417	-0.622
0.1	0.05	no	yes	yes	0.993	0.883	1.000	0.932	1.306	0.800	0.909	0.490
0.1	0.05	no	yes	no	0.993	0.883	1.000	0.932	0.495	0.167	0.324	0.034
0.1	0.05	no	no	yes	0.993	0.993	1.000	1.000	0.281	0.000	0.068	-0.166
0.1	0.05	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.219	-0.129	-0.320

Table 2 (p. 4 of 8: *M*=0.1, Tier 3). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 3							
					ABC RSPR		OFL RSPR		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.1	0.01	yes	yes	yes	0.371	0.371	0.327	0.327	0.111	0.000	-0.081	-0.172
0.1	0.01	yes	yes	no	0.371	0.371	0.327	0.327	0.000	-0.100	-0.157	-0.241
0.1	0.01	yes	no	yes	0.371	0.400	0.327	0.350	0.259	0.133	0.016	-0.085
0.1	0.01	yes	no	no	0.371	0.400	0.327	0.350	0.117	0.006	-0.076	-0.169
0.1	0.01	no	yes	yes	0.400	0.371	0.350	0.327	-0.006	-0.118	-0.177	-0.270
0.1	0.01	no	yes	no	0.400	0.371	0.350	0.327	-0.105	-0.206	-0.245	-0.330
0.1	0.01	no	no	yes	0.400	0.400	0.350	0.350	0.127	0.000	-0.090	-0.193
0.1	0.01	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.113	-0.173	-0.266
0.1	0.02	yes	yes	yes	0.345	0.345	0.307	0.307	0.220	0.000	0.010	-0.172
0.1	0.02	yes	yes	no	0.345	0.345	0.307	0.307	0.000	-0.181	-0.143	-0.298
0.1	0.02	yes	no	yes	0.345	0.400	0.307	0.350	0.598	0.309	0.250	0.024
0.1	0.02	yes	no	no	0.345	0.400	0.307	0.350	0.235	0.012	0.020	-0.165
0.1	0.02	no	yes	yes	0.400	0.345	0.350	0.307	-0.011	-0.236	-0.182	-0.368
0.1	0.02	no	yes	no	0.400	0.345	0.350	0.307	-0.190	-0.374	-0.306	-0.464
0.1	0.02	no	no	yes	0.400	0.400	0.350	0.350	0.295	0.000	0.013	-0.218
0.1	0.02	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.228	-0.174	-0.362
0.1	0.03	yes	yes	yes	0.323	0.323	0.289	0.289	0.329	0.000	0.100	-0.172
0.1	0.03	yes	yes	no	0.323	0.323	0.289	0.289	0.000	-0.248	-0.132	-0.347
0.1	0.03	yes	no	yes	0.323	0.400	0.289	0.350	1.064	0.553	0.548	0.165
0.1	0.03	yes	no	no	0.323	0.400	0.289	0.350	0.352	0.017	0.116	-0.161
0.1	0.03	no	yes	yes	0.400	0.323	0.350	0.289	-0.017	-0.356	-0.187	-0.467
0.1	0.03	no	yes	no	0.400	0.323	0.350	0.289	-0.261	-0.516	-0.358	-0.580
0.1	0.03	no	no	yes	0.400	0.400	0.350	0.350	0.527	0.000	0.145	-0.250
0.1	0.03	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.345	-0.175	-0.460
0.1	0.04	yes	yes	yes	0.303	0.303	0.273	0.273	0.437	0.000	0.189	-0.172
0.1	0.04	yes	yes	no	0.303	0.303	0.273	0.273	0.000	-0.304	-0.123	-0.389
0.1	0.04	yes	no	yes	0.303	0.400	0.273	0.350	1.749	0.913	0.943	0.352
0.1	0.04	yes	no	no	0.303	0.400	0.273	0.350	0.470	0.023	0.212	-0.157
0.1	0.04	no	yes	yes	0.400	0.303	0.350	0.273	-0.023	-0.477	-0.191	-0.568
0.1	0.04	no	yes	no	0.400	0.303	0.350	0.273	-0.320	-0.636	-0.403	-0.681
0.1	0.04	no	no	yes	0.400	0.400	0.350	0.350	0.870	0.000	0.321	-0.293
0.1	0.04	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.465	-0.176	-0.559
0.1	0.05	yes	yes	yes	0.285	0.285	0.258	0.258	0.543	0.000	0.277	-0.172
0.1	0.05	yes	yes	no	0.285	0.285	0.258	0.258	0.000	-0.352	-0.114	-0.426
0.1	0.05	yes	no	yes	0.285	0.400	0.258	0.350	2.855	1.498	1.492	0.615
0.1	0.05	yes	no	no	0.285	0.400	0.258	0.350	0.589	0.030	0.308	-0.153
0.1	0.05	no	yes	yes	0.400	0.285	0.350	0.258	-0.029	-0.600	-0.196	-0.669
0.1	0.05	no	yes	no	0.400	0.285	0.350	0.258	-0.371	-0.741	-0.442	-0.770
0.1	0.05	no	no	yes	0.400	0.400	0.350	0.350	1.426	0.000	0.568	-0.354
0.1	0.05	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.588	-0.177	-0.661

Table 2 (p. 5 of 8: *M*=0.2, Tier 2). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 2							
					ABC SY/MSY		OFL SY/MSY		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.2	0.02	yes	yes	yes	0.977	0.977	0.996	0.996	0.101	0.000	-0.083	-0.167
0.2	0.02	yes	yes	no	0.977	0.977	0.996	0.996	0.000	-0.092	-0.152	-0.230
0.2	0.02	yes	no	yes	0.977	0.992	0.996	1.000	-0.034	-0.122	-0.193	-0.267
0.2	0.02	yes	no	no	0.977	0.992	0.996	1.000	-0.111	-0.192	-0.246	-0.315
0.2	0.02	no	yes	yes	0.992	0.977	1.000	0.996	0.238	0.140	0.031	-0.051
0.2	0.02	no	yes	no	0.992	0.977	1.000	0.996	0.124	0.035	-0.046	-0.122
0.2	0.02	no	no	yes	0.992	0.992	1.000	1.000	0.086	0.000	-0.093	-0.165
0.2	0.02	no	no	no	0.992	0.992	1.000	1.000	0.000	-0.080	-0.152	-0.219
0.2	0.04	yes	yes	yes	0.957	0.957	0.986	0.986	0.200	0.000	-0.001	-0.167
0.2	0.04	yes	yes	no	0.957	0.957	0.986	0.986	0.000	-0.167	-0.139	-0.283
0.2	0.04	yes	no	yes	0.957	0.993	0.986	1.000	-0.067	-0.223	-0.219	-0.349
0.2	0.04	yes	no	no	0.957	0.993	0.986	1.000	-0.187	-0.323	-0.302	-0.418
0.2	0.04	no	yes	yes	0.993	0.957	1.000	0.986	0.477	0.287	0.230	0.072
0.2	0.04	no	yes	no	0.993	0.957	1.000	0.986	0.231	0.072	0.059	-0.077
0.2	0.04	no	no	yes	0.993	0.993	1.000	1.000	0.148	0.000	-0.039	-0.163
0.2	0.04	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.129	-0.140	-0.251
0.2	0.06	yes	yes	yes	0.933	0.933	0.970	0.970	0.297	0.000	0.080	-0.167
0.2	0.06	yes	yes	no	0.933	0.933	0.970	0.970	0.000	-0.229	-0.128	-0.328
0.2	0.06	yes	no	yes	0.933	0.993	0.970	1.000	-0.101	-0.307	-0.245	-0.418
0.2	0.06	yes	no	no	0.933	0.993	0.970	1.000	-0.244	-0.417	-0.344	-0.494
0.2	0.06	no	yes	yes	0.993	0.933	1.000	0.970	0.716	0.442	0.429	0.201
0.2	0.06	no	yes	no	0.993	0.933	1.000	0.970	0.323	0.112	0.154	-0.030
0.2	0.06	no	no	yes	0.993	0.993	1.000	1.000	0.190	0.000	-0.001	-0.160
0.2	0.06	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.160	-0.132	-0.270
0.2	0.08	yes	yes	yes	0.907	0.907	0.951	0.951	0.393	0.000	0.160	-0.167
0.2	0.08	yes	yes	no	0.907	0.907	0.951	0.951	0.000	-0.282	-0.118	-0.367
0.2	0.08	yes	no	yes	0.907	0.993	0.951	1.000	-0.133	-0.378	-0.270	-0.476
0.2	0.08	yes	no	no	0.907	0.993	0.951	1.000	-0.288	-0.489	-0.377	-0.553
0.2	0.08	no	yes	yes	0.993	0.907	1.000	0.951	0.957	0.606	0.629	0.338
0.2	0.08	no	yes	no	0.993	0.907	1.000	0.951	0.405	0.154	0.239	0.017
0.2	0.08	no	no	yes	0.993	0.993	1.000	1.000	0.218	0.000	0.026	-0.158
0.2	0.08	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.179	-0.125	-0.282
0.2	0.1	yes	yes	yes	0.880	0.880	0.930	0.930	0.486	0.000	0.237	-0.167
0.2	0.1	yes	yes	no	0.880	0.880	0.930	0.930	0.000	-0.327	-0.110	-0.401
0.2	0.1	yes	no	yes	0.880	0.994	0.930	1.000	-0.165	-0.438	-0.294	-0.525
0.2	0.1	yes	no	no	0.880	0.994	0.930	1.000	-0.324	-0.545	-0.404	-0.599
0.2	0.1	no	yes	yes	0.994	0.880	1.000	0.930	1.198	0.779	0.830	0.481
0.2	0.1	no	yes	no	0.994	0.880	1.000	0.930	0.479	0.197	0.316	0.066
0.2	0.1	no	no	yes	0.994	0.994	1.000	1.000	0.235	0.000	0.044	-0.155
0.2	0.1	no	no	no	0.994	0.994	1.000	1.000	0.000	-0.191	-0.119	-0.287

Table 2 (p. 6 of 8: *M*=0.2, Tier 3). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 3							
					ABC RSPR		OFL RSPR		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.2	0.02	yes	yes	yes	0.371	0.371	0.327	0.327	0.101	0.000	-0.083	-0.167
0.2	0.02	yes	yes	no	0.371	0.371	0.327	0.327	0.000	-0.092	-0.152	-0.230
0.2	0.02	yes	no	yes	0.371	0.400	0.327	0.350	0.242	0.128	0.009	-0.084
0.2	0.02	yes	no	no	0.371	0.400	0.327	0.350	0.113	0.011	-0.075	-0.160
0.2	0.02	no	yes	yes	0.400	0.371	0.350	0.327	-0.011	-0.114	-0.176	-0.262
0.2	0.02	no	yes	no	0.400	0.371	0.350	0.327	-0.101	-0.195	-0.238	-0.317
0.2	0.02	no	no	yes	0.400	0.400	0.350	0.350	0.116	0.000	-0.093	-0.188
0.2	0.02	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.104	-0.169	-0.256
0.2	0.04	yes	yes	yes	0.346	0.346	0.308	0.308	0.200	0.000	-0.001	-0.167
0.2	0.04	yes	yes	no	0.346	0.346	0.308	0.308	0.000	-0.167	-0.139	-0.283
0.2	0.04	yes	no	yes	0.346	0.400	0.308	0.350	0.558	0.298	0.225	0.021
0.2	0.04	yes	no	no	0.346	0.400	0.308	0.350	0.226	0.022	0.017	-0.153
0.2	0.04	no	yes	yes	0.400	0.346	0.350	0.308	-0.021	-0.230	-0.185	-0.358
0.2	0.04	no	yes	no	0.400	0.346	0.350	0.308	-0.185	-0.358	-0.298	-0.447
0.2	0.04	no	no	yes	0.400	0.400	0.350	0.350	0.270	0.000	-0.001	-0.214
0.2	0.04	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.213	-0.171	-0.347
0.2	0.06	yes	yes	yes	0.324	0.324	0.290	0.290	0.297	0.000	0.080	-0.167
0.2	0.06	yes	yes	no	0.324	0.324	0.290	0.290	0.000	-0.229	-0.128	-0.328
0.2	0.06	yes	no	yes	0.324	0.400	0.290	0.350	0.989	0.533	0.499	0.155
0.2	0.06	yes	no	no	0.324	0.400	0.290	0.350	0.340	0.033	0.109	-0.145
0.2	0.06	no	yes	yes	0.400	0.324	0.350	0.290	-0.032	-0.348	-0.194	-0.457
0.2	0.06	no	yes	no	0.400	0.324	0.350	0.290	-0.254	-0.497	-0.349	-0.562
0.2	0.06	no	no	yes	0.400	0.400	0.350	0.350	0.484	0.000	0.118	-0.247
0.2	0.06	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.326	-0.173	-0.443
0.2	0.08	yes	yes	yes	0.304	0.304	0.274	0.274	0.393	0.000	0.160	-0.167
0.2	0.08	yes	yes	no	0.304	0.304	0.274	0.274	0.000	-0.282	-0.118	-0.367
0.2	0.08	yes	no	yes	0.304	0.400	0.274	0.350	1.620	0.881	0.859	0.335
0.2	0.08	yes	no	no	0.304	0.400	0.274	0.350	0.456	0.045	0.201	-0.137
0.2	0.08	no	yes	yes	0.400	0.304	0.350	0.274	-0.043	-0.469	-0.203	-0.557
0.2	0.08	no	yes	no	0.400	0.304	0.350	0.274	-0.313	-0.618	-0.394	-0.664
0.2	0.08	no	no	yes	0.400	0.400	0.350	0.350	0.800	0.000	0.277	-0.291
0.2	0.08	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.444	-0.175	-0.542
0.2	0.1	yes	yes	yes	0.287	0.287	0.260	0.260	0.486	0.000	0.237	-0.167
0.2	0.1	yes	yes	no	0.287	0.287	0.260	0.260	0.000	-0.327	-0.110	-0.401
0.2	0.1	yes	no	yes	0.287	0.400	0.260	0.350	2.638	1.448	1.357	0.586
0.2	0.1	yes	no	no	0.287	0.400	0.260	0.350	0.572	0.058	0.294	-0.129
0.2	0.1	no	yes	yes	0.400	0.287	0.350	0.260	-0.055	-0.592	-0.213	-0.660
0.2	0.1	no	yes	no	0.400	0.287	0.350	0.260	-0.364	-0.725	-0.434	-0.755
0.2	0.1	no	no	yes	0.400	0.400	0.350	0.350	1.315	0.000	0.500	-0.352
0.2	0.1	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.568	-0.177	-0.644

Table 2 (p. 7 of 8: *M*=0.3, Tier 2). Exploration of total catch accounting. See text for explanation.

		F1 assumes F2=0?		Specs exclude C2?	Tier 2							
					ABC SY/MSY		OFL SY/MSY		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.3	0.03	yes	yes	yes	0.977	0.977	0.996	0.996	0.092	0.000	-0.085	-0.162
0.3	0.03	yes	yes	no	0.977	0.977	0.996	0.996	0.000	-0.084	-0.147	-0.219
0.3	0.03	yes	no	yes	0.977	0.992	0.996	1.000	-0.036	-0.117	-0.189	-0.257
0.3	0.03	yes	no	no	0.977	0.992	0.996	1.000	-0.106	-0.181	-0.236	-0.301
0.3	0.03	no	yes	yes	0.992	0.977	1.000	0.996	0.221	0.133	0.023	-0.051
0.3	0.03	no	yes	no	0.992	0.977	1.000	0.996	0.118	0.037	-0.046	-0.116
0.3	0.03	no	no	yes	0.992	0.992	1.000	1.000	0.078	0.000	-0.093	-0.159
0.3	0.03	no	no	no	0.992	0.992	1.000	1.000	0.000	-0.073	-0.146	-0.208
0.3	0.06	yes	yes	yes	0.956	0.956	0.986	0.986	0.182	0.000	-0.010	-0.162
0.3	0.06	yes	yes	no	0.956	0.956	0.986	0.986	0.000	-0.154	-0.134	-0.268
0.3	0.06	yes	no	yes	0.956	0.992	0.986	1.000	-0.071	-0.214	-0.215	-0.336
0.3	0.06	yes	no	no	0.956	0.992	0.986	1.000	-0.180	-0.306	-0.289	-0.398
0.3	0.06	no	yes	yes	0.992	0.956	1.000	0.986	0.440	0.272	0.207	0.066
0.3	0.06	no	yes	no	0.992	0.956	1.000	0.986	0.219	0.077	0.055	-0.068
0.3	0.06	no	no	yes	0.992	0.992	1.000	1.000	0.132	0.000	-0.044	-0.155
0.3	0.06	no	no	no	0.992	0.992	1.000	1.000	0.000	-0.117	-0.134	-0.235
0.3	0.09	yes	yes	yes	0.933	0.933	0.970	0.970	0.269	0.000	0.063	-0.162
0.3	0.09	yes	yes	no	0.933	0.933	0.970	0.970	0.000	-0.212	-0.124	-0.309
0.3	0.09	yes	no	yes	0.933	0.993	0.970	1.000	-0.106	-0.295	-0.242	-0.402
0.3	0.09	yes	no	no	0.933	0.993	0.970	1.000	-0.234	-0.396	-0.329	-0.471
0.3	0.09	no	yes	yes	0.993	0.933	1.000	0.970	0.657	0.419	0.388	0.189
0.3	0.09	no	yes	no	0.993	0.933	1.000	0.970	0.306	0.119	0.144	-0.020
0.3	0.09	no	no	yes	0.993	0.993	1.000	1.000	0.167	0.000	-0.010	-0.152
0.3	0.09	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.143	-0.124	-0.250
0.3	0.12	yes	yes	yes	0.907	0.907	0.951	0.951	0.353	0.000	0.134	-0.162
0.3	0.12	yes	yes	no	0.907	0.907	0.951	0.951	0.000	-0.261	-0.114	-0.345
0.3	0.12	yes	no	yes	0.907	0.993	0.951	1.000	-0.140	-0.365	-0.267	-0.458
0.3	0.12	yes	no	no	0.907	0.993	0.951	1.000	-0.277	-0.466	-0.361	-0.528
0.3	0.12	no	yes	yes	0.993	0.907	1.000	0.951	0.871	0.574	0.568	0.319
0.3	0.12	no	yes	no	0.993	0.907	1.000	0.951	0.383	0.163	0.225	0.030
0.3	0.12	no	no	yes	0.993	0.993	1.000	1.000	0.189	0.000	0.013	-0.148
0.3	0.12	no	no	no	0.993	0.993	1.000	1.000	0.000	-0.159	-0.116	-0.256
0.3	0.15	yes	yes	yes	0.880	0.880	0.930	0.930	0.435	0.000	0.203	-0.162
0.3	0.15	yes	yes	no	0.880	0.880	0.930	0.930	0.000	-0.303	-0.106	-0.377
0.3	0.15	yes	no	yes	0.880	0.994	0.930	1.000	-0.174	-0.424	-0.292	-0.507
0.3	0.15	yes	no	no	0.880	0.994	0.930	1.000	-0.311	-0.520	-0.386	-0.572
0.3	0.15	no	yes	yes	0.994	0.880	1.000	0.930	1.083	0.737	0.746	0.456
0.3	0.15	no	yes	no	0.994	0.880	1.000	0.930	0.451	0.210	0.298	0.082
0.3	0.15	no	no	yes	0.994	0.994	1.000	1.000	0.199	0.000	0.028	-0.143
0.3	0.15	no	no	no	0.994	0.994	1.000	1.000	0.000	-0.166	-0.109	-0.257

Table 2 (p. 8 of 8: *M*=0.3, Tier 3). Exploration of total catch accounting. See text for explanation.

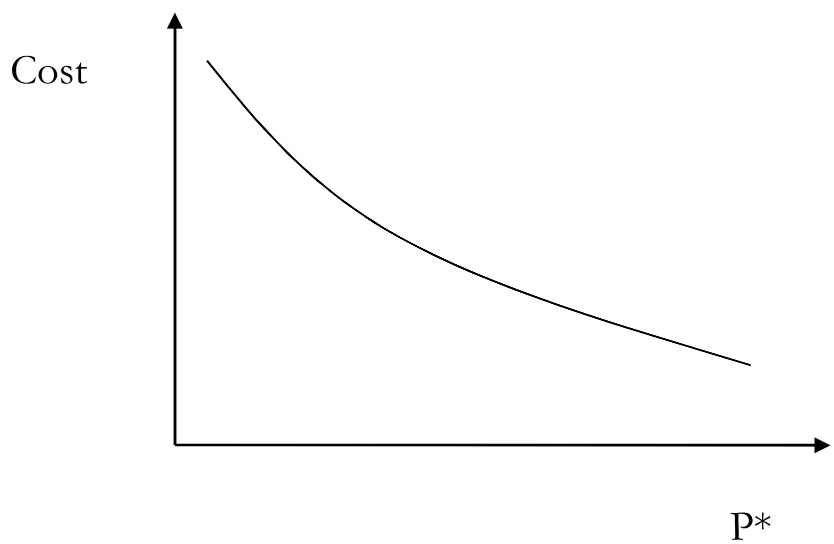
		F1 assumes F2=0?		Specs exclude C2?	Tier 3							
					ABC RSPR		OFL RSPR		ABC overage		OFL overage	
M	F2	Catch	Specs	C2?	Catch	Specs	Catch	Specs	C1+C2	C1	C1+C2	C1
0.3	0.03	yes	yes	yes	0.371	0.371	0.328	0.328	0.092	0.000	-0.085	-0.162
0.3	0.03	yes	yes	no	0.371	0.371	0.328	0.328	0.000	-0.084	-0.147	-0.219
0.3	0.03	yes	no	yes	0.371	0.400	0.328	0.350	0.227	0.123	0.002	-0.082
0.3	0.03	yes	no	no	0.371	0.400	0.328	0.350	0.109	0.015	-0.074	-0.152
0.3	0.03	no	yes	yes	0.400	0.371	0.350	0.328	-0.015	-0.110	-0.174	-0.254
0.3	0.03	no	yes	no	0.400	0.371	0.350	0.328	-0.098	-0.185	-0.231	-0.305
0.3	0.03	no	no	yes	0.400	0.400	0.350	0.350	0.107	0.000	-0.096	-0.183
0.3	0.03	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.096	-0.165	-0.245
0.3	0.06	yes	yes	yes	0.346	0.346	0.308	0.308	0.182	0.000	-0.010	-0.162
0.3	0.06	yes	yes	no	0.346	0.346	0.308	0.308	0.000	-0.154	-0.134	-0.268
0.3	0.06	yes	no	yes	0.346	0.400	0.308	0.350	0.520	0.287	0.203	0.018
0.3	0.06	yes	no	no	0.346	0.400	0.308	0.350	0.218	0.031	0.014	-0.142
0.3	0.06	no	yes	yes	0.400	0.346	0.350	0.308	-0.030	-0.223	-0.187	-0.349
0.3	0.06	no	yes	no	0.400	0.346	0.350	0.308	-0.179	-0.342	-0.290	-0.431
0.3	0.06	no	no	yes	0.400	0.400	0.350	0.350	0.248	0.000	-0.013	-0.209
0.3	0.06	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.199	-0.167	-0.333
0.3	0.09	yes	yes	yes	0.324	0.324	0.291	0.291	0.269	0.000	0.063	-0.162
0.3	0.09	yes	yes	no	0.324	0.324	0.291	0.291	0.000	-0.212	-0.124	-0.309
0.3	0.09	yes	no	yes	0.324	0.400	0.291	0.350	0.920	0.514	0.455	0.147
0.3	0.09	yes	no	no	0.324	0.400	0.291	0.350	0.329	0.048	0.103	-0.131
0.3	0.09	no	yes	yes	0.400	0.324	0.350	0.291	-0.046	-0.339	-0.200	-0.446
0.3	0.09	no	yes	no	0.400	0.324	0.350	0.291	-0.248	-0.479	-0.341	-0.544
0.3	0.09	no	no	yes	0.400	0.400	0.350	0.350	0.445	0.000	0.095	-0.243
0.3	0.09	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.308	-0.170	-0.426
0.3	0.12	yes	yes	yes	0.305	0.305	0.276	0.276	0.353	0.000	0.134	-0.162
0.3	0.12	yes	yes	no	0.305	0.305	0.276	0.276	0.000	-0.261	-0.114	-0.345
0.3	0.12	yes	no	yes	0.305	0.400	0.276	0.350	1.504	0.850	0.784	0.319
0.3	0.12	yes	no	no	0.305	0.400	0.276	0.350	0.442	0.065	0.192	-0.119
0.3	0.12	no	yes	yes	0.400	0.305	0.350	0.276	-0.061	-0.460	-0.213	-0.547
0.3	0.12	no	yes	no	0.400	0.305	0.350	0.276	-0.306	-0.601	-0.386	-0.646
0.3	0.12	no	no	yes	0.400	0.400	0.350	0.350	0.737	0.000	0.238	-0.287
0.3	0.12	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.424	-0.173	-0.524
0.3	0.15	yes	yes	yes	0.288	0.288	0.262	0.262	0.435	0.000	0.203	-0.162
0.3	0.15	yes	yes	no	0.288	0.288	0.262	0.262	0.000	-0.303	-0.106	-0.377
0.3	0.15	yes	no	yes	0.288	0.400	0.262	0.350	2.444	1.400	1.238	0.559
0.3	0.15	yes	no	no	0.288	0.400	0.262	0.350	0.556	0.084	0.282	-0.107
0.3	0.15	no	yes	yes	0.400	0.288	0.350	0.262	-0.077	-0.583	-0.227	-0.651
0.3	0.15	no	yes	no	0.400	0.288	0.350	0.262	-0.357	-0.710	-0.425	-0.740
0.3	0.15	no	no	yes	0.400	0.400	0.350	0.350	1.214	0.000	0.439	-0.350
0.3	0.15	no	no	no	0.400	0.400	0.350	0.350	0.000	-0.548	-0.176	-0.628

Appendix: ACLs and Maximum Economic Yield

By Michael Dalton (based on work with André Punt and David Tomberlin)

National Standard 1 states that *Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry.* In this statement, OY is an objective and the prevention of overfishing is a constraint. In general, OY can be influenced by risk preferences or harvest methods or institutions. Each of these can affect benefits and costs, distributions of these, as well as risk and uncertainty. In practice, OY is defined relative to MSY which under MSA Section 3(33): OY is *the amount of fish which … is prescribed as such on the basis of the maximum sustainable yield from the fishery, as reduced by any relevant economic, social, or ecological factors.* This raises questions about these factors and in general whether MSY is necessarily a 'good' objective? For example, what about fishing costs, or the role of prices in evaluating benefits of yield or how should risk and uncertainty be treated (see Fig 1)? In general, the risk of overfishing depends on choice of P*, and P* < 1/2 incurs a cost in terms of foregone catch. Cost curves of this type were considered in the NPFMC crab ACL analysis.

Fig. 1: General cost of reducing overfishing risk P* in terms of foregone catch.



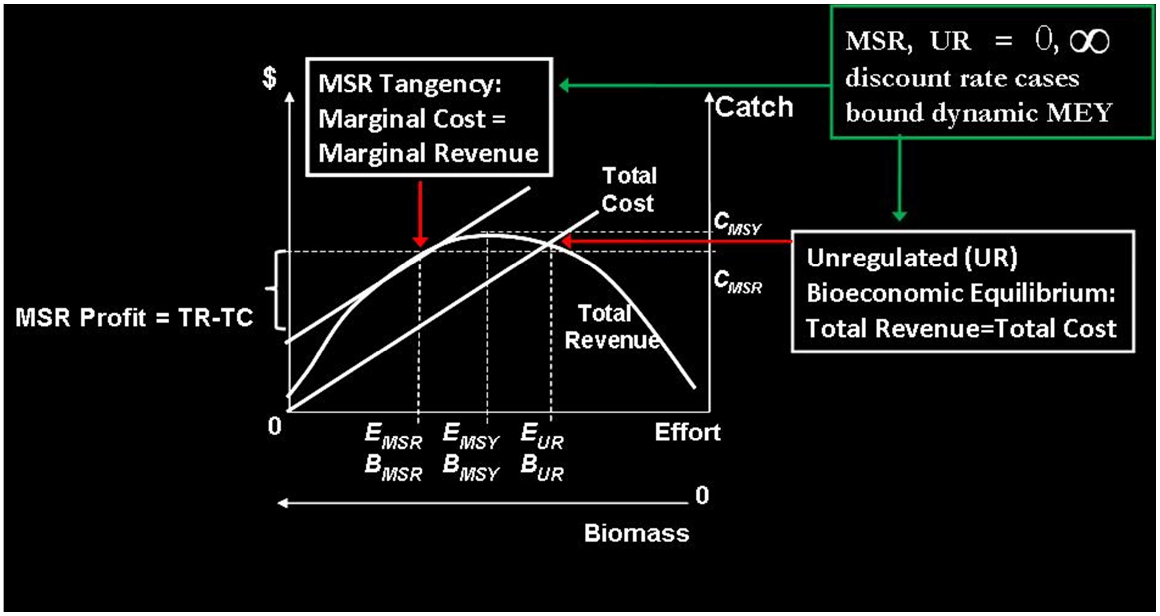
Under some conditions, however, economic benefits of reducing catch below MSY can outweigh the cost of foregone harvest which opens possibility of win-win outcomes. Under these conditions, the economic optimum is achieved at maximum economic yield (MEY).

Recent scientific interest in Maximum Economic Yield (MEY):

- On implementing maximum economic yield in commercial fisheries (Dichmont, Pascoe, Kompas, Punt, Deng, PNAS 2010)
- Economics of overexploitation revisited (Grafton, Kompas, Hilborn, Science 2007)
- Limits to the privatization of fishery resources (Clark, Munro, Sumaila, Land Economics 2010)

- Limits to the privatization of fishery resources: Comment
  (Grafton, Kompas, Hilborn, Land Economics 2010)
- Limits to the privatization of fishery resources: Reply
  (Clark, Munro, Sumaila, Land Economics 2010)

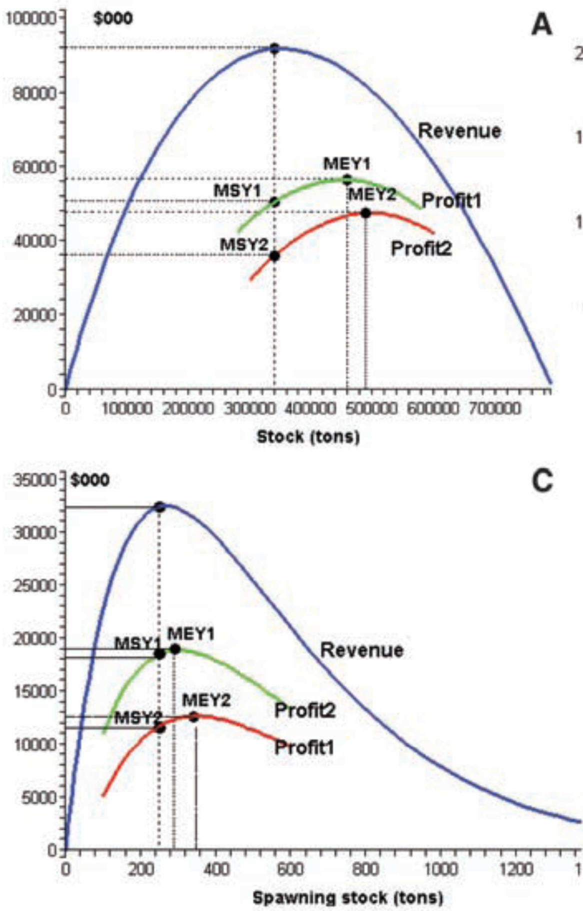
Fig.2: Maximum Sustainable Rent (MSR) is static MEY in Gordon-Schaefer bioeconomic model



The classic inequality of the Gordon-Schaefer (GS) model is $B_{MSR} > B_{MSY}$ unless Marginal Cost = 0, and then $B_{MSR} = B_{MSY}$, if and only if, $C_{MSR} < C_{MSY}$ unless MC = 0 then $C_{MSR} = C_{MSY}$

Grafton et al. (2007) consider dynamic MEY in Gordon-Schaefer type bioeconomic model and find that classic inequality $B_{MEY} > B_{MSY}$ holds in 4 empirical cases that were analyzed. Therefore, Grafton et al. (2007) conclude that fishery management based on a dynamic MEY control rule can promise win-win outcomes with respect to MSY control rules because MEY has a better economic return and, like static MSR in GS model, is biologically more conservative than MSY.

Fig. 3: (A) B_{MEY} and B_{MSY} of Western and Central Pacific big eye tuna. (B) B_{MEY} and B_{MSY} of Western and Central Pacific yellowfin tuna. (C) B_{MEY} and B_{MSY} of Australian northern prawn fishery. (D) B_{MEY} and B_{MSY} of Australian orange roughy fishery.



Source: Grafton et al. 2007, Economics of Overexploitation Revisited, Science 318:1601.

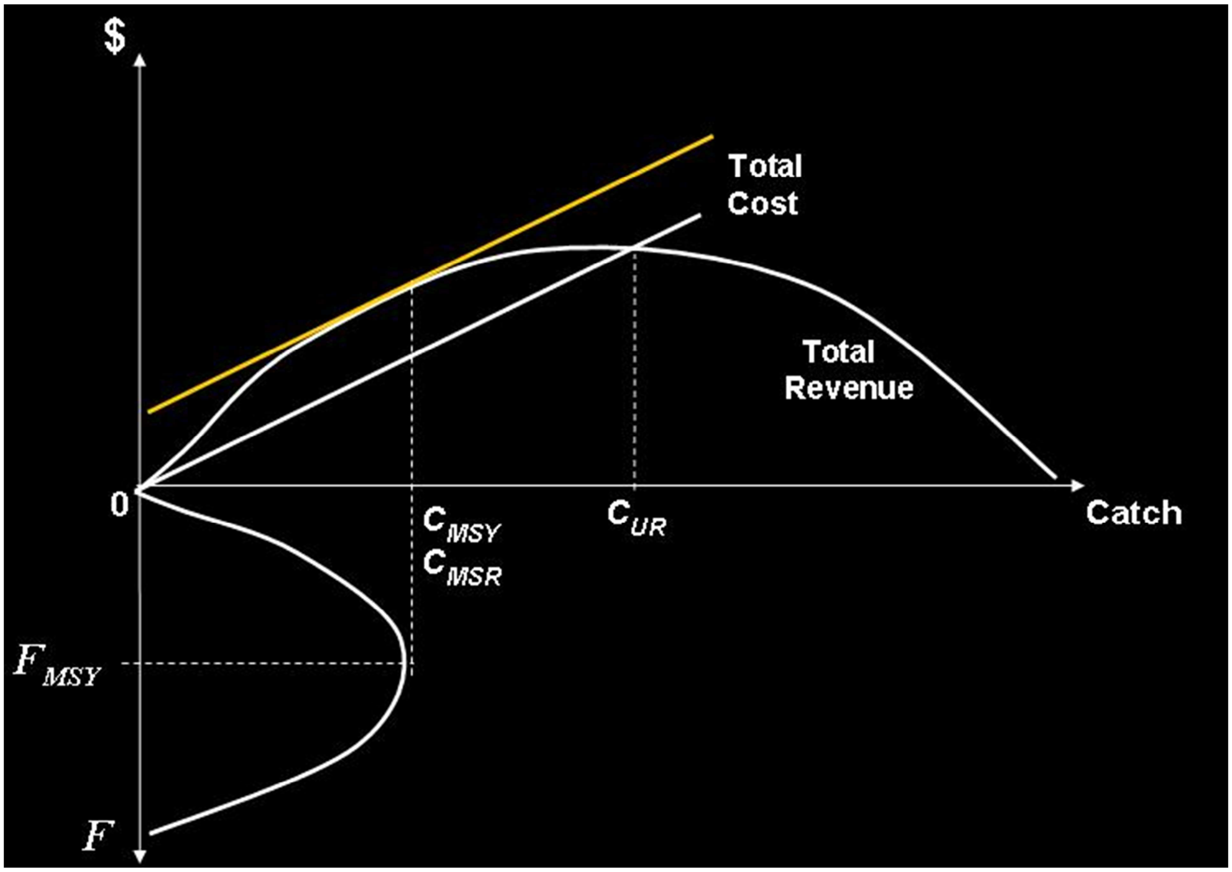
However the conclusions of Grafton et al. (2007) depend on underlying assumptions, including the Schaefer catch equation in which catch is the product of effort, biomass, and a catchability coefficient. Clark et al. (2010) criticize results of Grafton et al. (2007) on the basis of these assumptions.

In addition, Grafton et al. (2007) does not consider age or size structured population dynamics, nor does it consider effects of changing market prices on MEY. Dichmont et al. (2010) incorporate a realistic treatment of population dynamics in a model based on Schaefer catch equation and do not consider effects of catch levels on market equilibrium prices which can matter for large fisheries such as Bering Sea pollock.

An alternative and in some ways much simpler bioeconomic model is proposed here that:

1. Incorporates population dynamics through an equilibrium yield curve
2. Relaxes strong assumption of Schaefer catch equation (e.g., catch proportional to effort)
3. Includes market equilibrium price effects with an explicit demand function

Fig. 4: Population dynamics and industry market equilibrium in static MEY alternative to the Gordon-Schaefer model.



In the alternative bioeconomic model depicted in Fig. 4, the equilibrium yield curve is derived in the usual way from an age or size structured population dynamics model, and in particular, shape of the yield curve is determined by an explicit assumption about the recruitment function (e.g., Ricker, Beverton-Holt). In addition, fishing effort is implicit and catch is the control variable. In practice, using catch as the control variable avoids having to make an explicit assumption for the relationship between catch and effort (e.g., Schaefer catch equation). The trade off is that costs must be represented in terms of catch (i.e., output) but that type of formulation is perfectly consistent with microeconomic principles. Like the GS model, costs are linear and revenues are quadratic. Unlike the GS model, revenues are quadratic in Fig. 4 because a linear demand function is assumed whereas prices are held constant in the GS model.

The type of bioeconomic model that is represented in Fig. 4 can lead to completely different conclusions from the GS model and provides a something of a counter-example:

- $C_{UR} > C_{MSY}$ and therefore C_{UR} is not sustainable in Fig. 4!
- $C_{MSY} = C_{MSR}$ by construction in Fig. 4!
- If marginal costs decrease (i.e., total cost curve becomes flatter) in Fig. 4 then $C_{MSY} < C_{MSR}$ and in that case the implied MSR would not be sustainable!

The last bullet above implies that the classic GS inequality $B_{MEY}>B_{MSY}$ does not necessarily hold if assumption of Schaefer catch equation is violated. In fact, Fig. 4 implies that the classic inequality is a special case and holds only if the price elasticity of demand is sufficiently small or marginal costs are sufficiently high. Note that curvature in the total revenue curve in Fig. 4 is determined by a linear demand function for catch, and not by a logistic growth function as it is in the GS model.

The static model depicted in Fig. 4 fully generalizes to dynamic market based industry equilibrium with stochastic processes that drive prices and recruitment. This equilibrium is formally characterized by decision rules that solve a dynamic optimization problem under uncertainty subject to stochastic prices and population dynamics with stochastic recruitments. This type of bioeconomic model is represented by an optimal control problem and the decision rules that solve this problem are stochastic processes that depend on prices and recruitments.

$$\underset{\{C_t \geq 0\}}{\text{Max}}\ \mathrm{E}\left\{\sum_{t=0}^{\infty}\beta^t\left(V_t' C_t - \frac{1}{2}(C_t - C_{t-1})'\mathbf{A}(C_t - C_{t-1})\right)\right\}$$

$$\text{s.t. } N_t = \mathbf{GM}N_{t-1} - \mathbf{GM}^{\frac{1}{2}}C_{t-1} + R_t$$

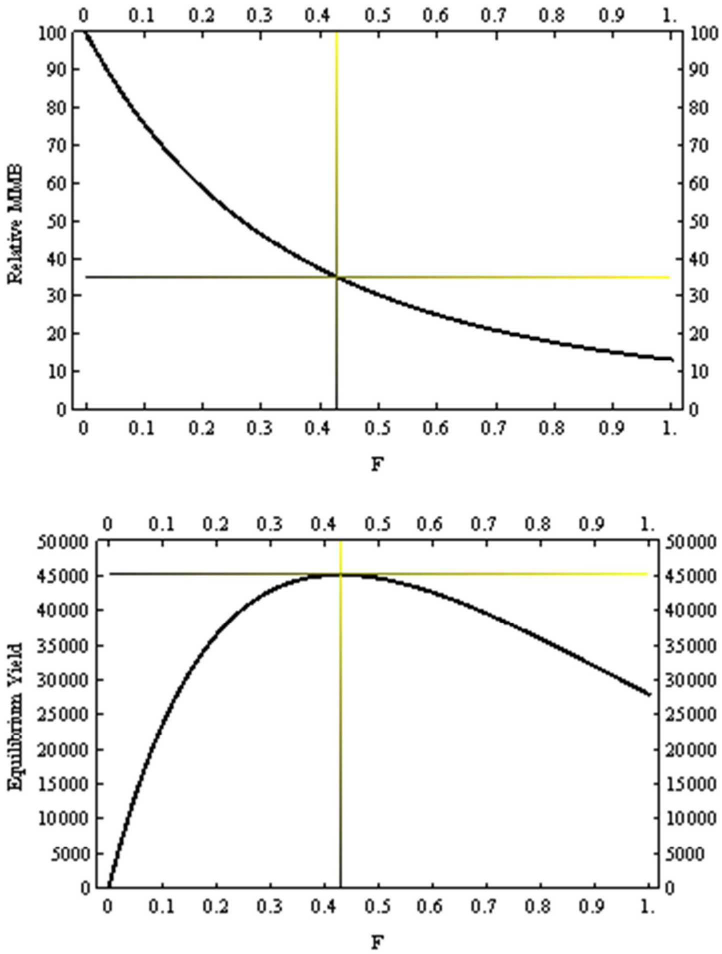
$$V_t = P_t - \theta - \mathbf{\Psi}C_t + \mathbf{\Phi}N_t$$

- Catch (at size) vector C_t is control and numbers (at size) N_t is state
- Net value per unit catch (at size) vector V_t taken as given by fishermen
- Base prices P_t and recruitments R_t are exogenous stochastic processes
- $0 < \beta < 1$ is the discount factor and θ is a vector of cost parameters;
- **G**, **M** are (lower triangular) growth, (diagonal) net mortality matrices
- Dynamic adjustment cost matrix **A**, demand elasticity $\mathbf{\Psi}$, and stock effect $\mathbf{\Phi}$
- Except for matrices (in bold), variables are random vectors
- Baranov, Pope's approximation used to get population dynamics in catch-explicit form
- Selectivity vector implies a scalar control problem in F
- Solution is summarized by an intertemporal decision rule

The intertemporal decision rule that solves the optimal control problem above implies time series of fishing mortalities $F_t(\omega)$ for which $F_t(\omega) > F_{MSY}$ or $F_t(\omega) < F_{MSY}$ are possible events. In this case, there is an explicit and well defined probability function $\Pr(\omega|\square)$ that measures likelihoods of these events.

While cost data for EBS snow crab fishery exist, these were not in form suitable for the analysis here. Instead, the cost parameter θ was set such that the long run stationary MEY catch level in the bioeconomic model was equal to MSY from the simple population dynamics model (i.e., $F_{MSY} \approx 0.43$; see Fig. 5).

Fig. 5: Mature male biomass and equilibrium yield (tons) with MSY (F35%) in simple EBS snow crab population dynamics model under Beverton-Holt recruitments.

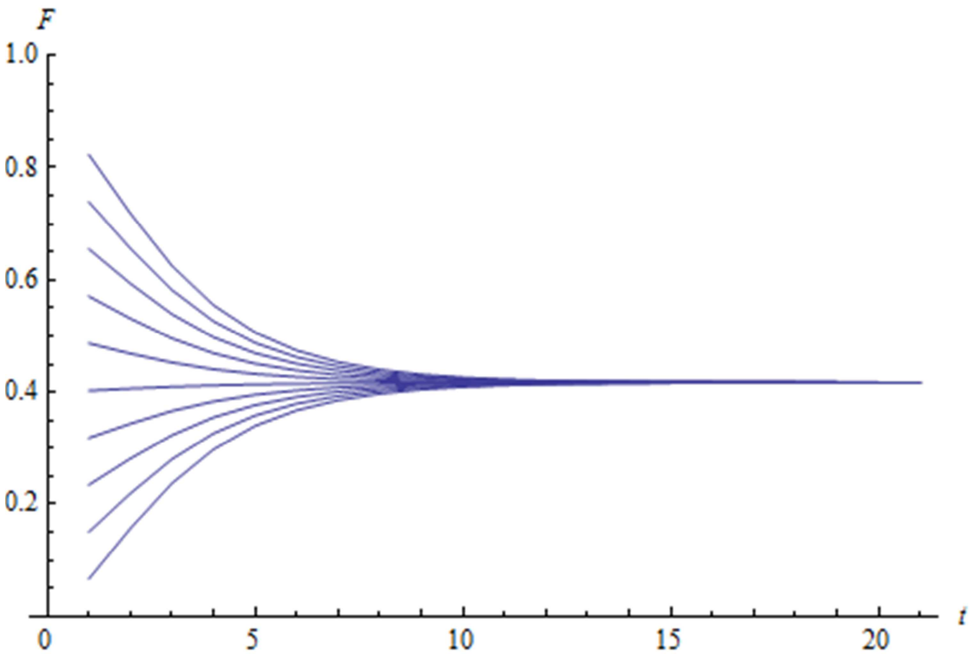


To make the bioeconomic model above operational, matrices **G** and **M** were parameterized based on a simple (5 size-classes, males only) version of the EBS snow crab population dynamics model that was used to compute the yield curve in Fig. 5. To keep the analysis as simple as possible here, a deterministic version of the model was considered but this restriction is easily relaxed. In the deterministic version,

- Base ex-vessel prices are held constant at \$2 per crab, loosely based on the historical average from CFEC fish tickets;
- Recruitments are held constant at $1.9\text{x}10^6$ per year based on recruitments at the unfished equilibrium from the simple snow crab population dynamics model;
- No stock externality is assumed (i.e., $\mathbf{\Phi}$ is a matrix of zeros) and bycatch in the groundfish fishery is ignored;
- Price elasticity of demand is assumed to be very elastic (i.e., $\mathbf{\Psi}$ is a small scalar times the identity matrix) which is supported historically (“An international supply and demand model for Alaska snow crab” by Greenberg, Hermann, McCracken, Marine Resource Economics 1995).

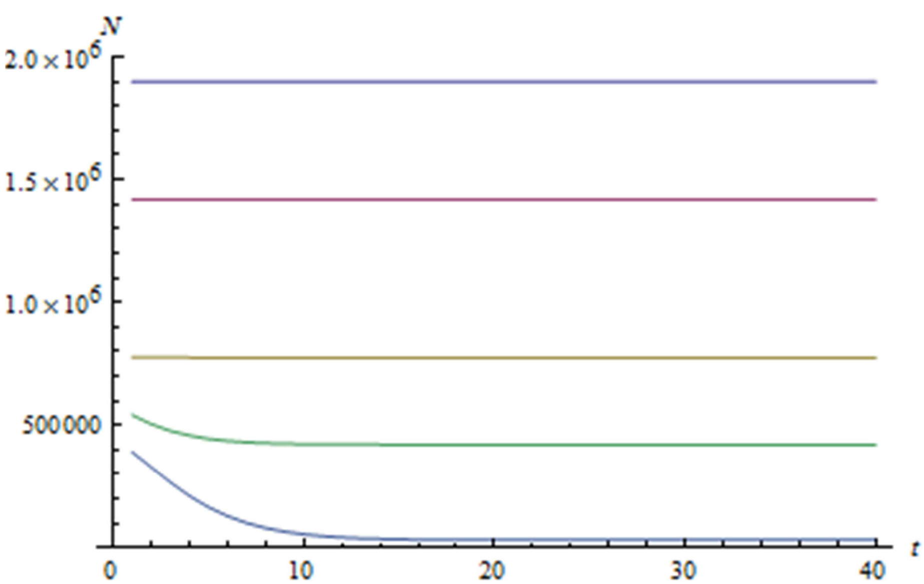
Dynamic MEY trajectories were computed starting from different initial conditions and each converges to F_{MSY} over time (see Fig. 6).

Fig. 6: Optimal dynamics to F_{MSY} starting from different initial conditions.



The final step in this analysis is to examine in more detail the dynamic MEY of developing a fishery from the pristine unfished state, which corresponds to the lowest curve in Fig. 6. In this case, the dynamics of each size class are presented in Fig. 7.

Fig. 7: Dynamic MEY numbers of crab in each size-class starting from the unfished initial condition (smallest size-class on top, largest size-class at bottom).



General conclusions can be drawn from the results above about the relationship between ACLs and MEY. One is that the inequality $B_{MEY} > B_{MSY}$ that is usually associated with bioeconomic models depends critically on assumptions implicit in Schafer's catch equation, or standard generalizations of it (e.g., see Grafton et al., 2007 or Clark et al., 2010). These assumptions may not be appropriate for Alaska fisheries, especially those that have been rationalized. For example, evidence suggests that the Gulf of Alaska sablefish fishery began exhibiting a hyperstable CPUE relationship following rationalization, which is not exactly consistent with Schaefer's catch equation. In general, the relationship between stock and catch in Schaefer's catch equation may not be appropriate for schooling species, or when fishermen target spawning aggregations. In these cases, the inequality $B_{MEY} > B_{MSY}$ may not hold and then the justification of reducing catch below MSY as a win-win outcome for economics and biology is false.

One type of bioeconomic equilibrium considered above is a decentralized stochastic dynamic MEY with limited entry that does not account for dynamic (stock) externalities in its optimality conditions, or the potential for coordinated monopolistic pricing to boost industry profits. In particular, this type of bioeconomic equilibrium is not in general an economic optimum for the industry as a whole because the stock externality, in particular, is not addressed. The stock externality here is the traditional one in fisheries economics that has been analyzed extensively in economics literature.

The conservation and economic benefits of monopolistic pricing are not normally considered in resource management. For example, constant prices are a standard assumption in bioeconomic models. But monopolistic pricing could be a win-win for biological conservation and the economics of some Alaska fisheries such as pollock. In general, monopolistic behavior restricts output and exploits the demand relationship to drive up prices. That drives a wedge between market prices and the marginal cost of production which is not economically efficient from a global perspective. But Alaska groundfish products are heavily exported and in this case monopolistic pricing may be consistent with Magnuson-Stevens Act objective of "maximizing net benefits to the nation." In this case, econometric estimates of global demand function parameters for Alaska groundfish products would be needed and these demand models would be coupled with parameters from simplified population dynamics models to quantify the alternative bioeconomic models described above.